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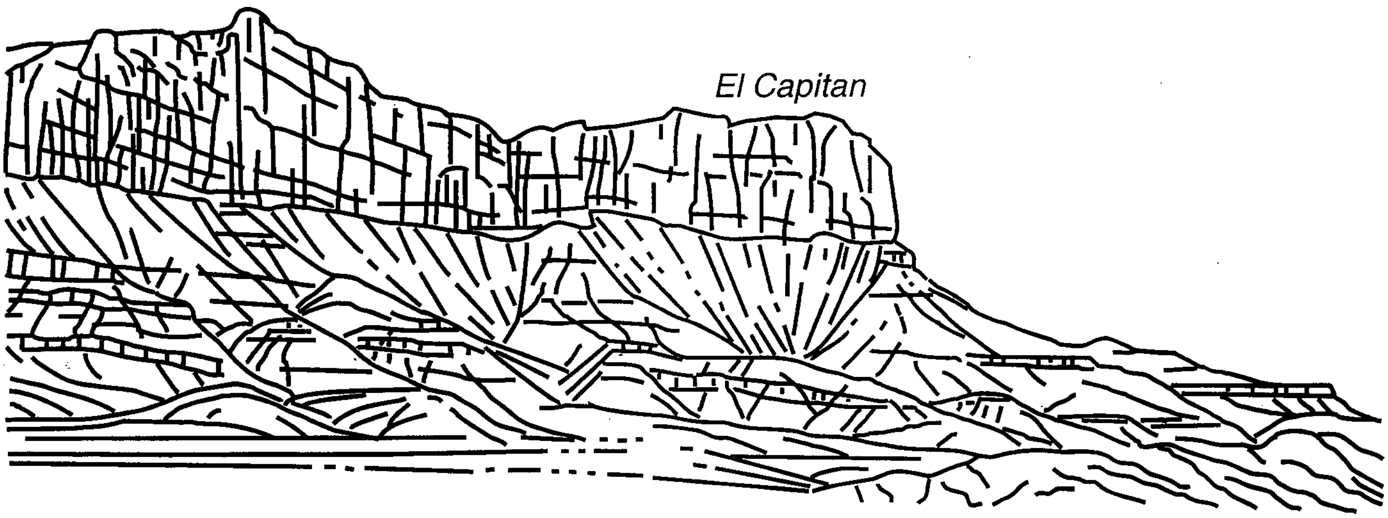
GEOLOGIC FRAMEWORK OF THE CAPITAN REEF



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SUBSURFACE EXPRESSION OF THE CAPITAN DEPOSITIONAL SYSTEM AND IMPLICATIONS FOR HYDROCARBON RESERVOIRS, NORTHEASTERN DELAWARE BASIN

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ABSTRACT: The Capitan depositional system was studied in the subsurface using seismic and well data from the northeastern Delaware basin. Seismic data of the Capitan depositional system show characteristics that include (1) a massive prograding reef/slope, (2) back-reef/shelf reflectors that dip and diverge basinward before disappearing into the massive reef, and (3) layered bottomset beds that thicken basinward by the addition of younger reflectors. A wireline log cross-section of nearby wells illustrates the stratigraphy in more detail than the seismic line. Basinward-dipping shelf strata are interbedded sandstones and carbonates that diverge and pass basinward into massive carbonate of the reef. Correlative markers within the massive reef are difficult to find. Slope carbonate beds thin and basinal siliciclastics thicken toward the basin. Bottomset beds in the basin consist of interbedded sandstones/siltstones and low-porosity carbonates. This subsurface stratigraphy is very similar to outcrop stratigraphy described in the Guadalupe Mountains.

Lithologic differences between outcrops and their subsurface equivalents are due largely to variations in dolomitization and evaporite dissolution on outcrops. Distribution of porosity in the Capitan depositional system is closely related to depositional facies. Back-reef sandstones and some shelf carbonates adjacent to the reef have good porosity and moderate permeability, but porosity and permeability in those strata generally decrease landward. The subsurface Capitan reef has moderate porosity and high permeability and is a regional aquifer. Carbonate beds in the basin are generally not porous, but some basinal sandstones filling elongate channels have good porosity and moderate permeability.

Hydrocarbons are not present in the Capitan reef because it does not occur in a setting that allows structural or stratigraphic closure and/or isolation from active meteoric aquifers. Many oil fields (10-400 million barrels recoverable) occur in back-reef equivalents of the Capitan reef, primarily the Seven Rivers and Yates formations, on the Northwestern Shelf and western edge of the Central Basin Platform. Those reservoirs are generally in stratigraphic or combination stratigraphic-structural traps, where porous and permeable sandstones pass up-dip into impermeable sandstones/siltstones, carbonates, and/or evaporites. Oil also occurs in channelized basinal sandstones equivalent to the reef, but the basinal fields have <5–30 million barrels of oil recoverable, and hence are generally smaller than those of the back-reef.

INTRODUCTION

The Capitan shelf margin is the youngest of a series of Permian shelf-margin complexes developed around the Delaware Basin (King, 1948; Newell et al., 1953). The trend of three of these margins, the Abo, Goat Seep, and Capitan, around the northern end of the basin, illustrates the long-term progradational history of the basin margin (Fig. 1). Outcrops of the Capitan depositional system (Capitan shelf margin and its shelf and basin equivalents) in the Guadalupe and Delaware Mountains of west Texas and southeastern New Mexico are some of the most studied and most frequently visited outcrops in the world. The allure of these outcrops is in part due to their exquisite nature, and also to their close proximity to a major hydrocarbon province, the Permian Basin. The purposes of this paper are: (1) to describe the subsurface expression of the Capitan depositional system using seismic and well data; (2) compare that subsurface expression to outcrop data from the Guadalupe Mountains; and (3) summarize hydrocarbon production from the Capitan depositional system.

Formation names applied to the rock units of the Capitan depositional system are shown in Fig. 2. Those stratigraphic units are based on the work of King (1948), Newell et al. (1953), and Hayes (1964). The Capitan Formation includes carbonates deposited in reef, forereef, and slope environments. Shelfal equivalents of the Capitan are bedded carbonates, siliciclastics, and evaporites of the Seven Rivers, Yates, and Tansill (youngest) formations. The basinal equivalent of the Capitan Formation is the Bell Canyon Formation, which is dominantly siliciclastic. The Bell Canyon Formation contains carbonate interbeds (Hegler, Pinery, Rader, McCombs, and Lamar, in ascending order) along the basin edge.

PREVIOUS STUDIES

Because the Capitan reef is not a hydrocarbon reservoir, subsurface studies of it are scarce. In contrast, there are several subsurface studies of the shelf and basin equivalents of the reef. Hill (1996) published a comprehensive review of outcrop and subsurface data that discusses facies, diagenesis, and several long-standing controversies regarding the Capitan depositional system. Garber et al. (1989) described lithologies, facies, and diagenesis of back-reef, reef, slope, and basinal strata cored in the Gulf PDB-04 well (see Fig. 1 for location). They also developed a gross stratigraphic framework for the Capitan shelf margin in the subsurface that included maps, seismic lines, and well log cross-sections.

Other subsurface studies of the Capitan depositional system generally concentrated on the lithologies and reservoir quality of either back-reef or basinal strata. Back-reef and shelf interior strata equivalent to the Capitan reef have been described in the subsurface by Crawford and Dunham (1982), Ordonez (1984), Ward et al. (1986), Garber et al. (1989), Borer and Harris (1991a, b), Andreason (1992), and Broadhead (1993a). The basin equivalent of the Capitan reef is described in the subsurface by Hull

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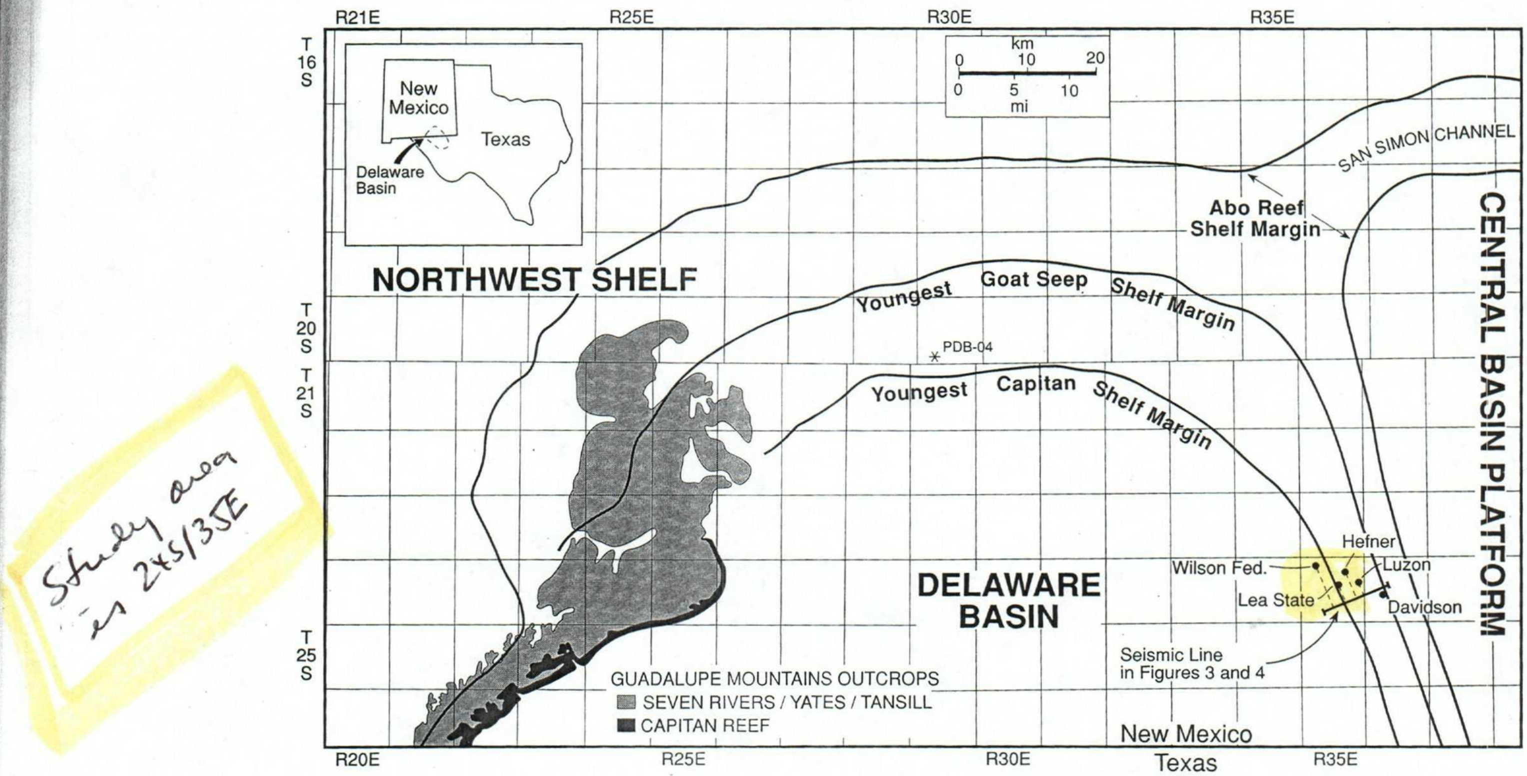

FIG. 1.—Map of northern Delaware Basin showing location of seismic line and well data included in this paper. Location of Guadalupe Mountains outcrops and Gulf PDB-04 well are also shown. Map indicates the long-term progradational history by showing the positions of the youngest shelf margins of the Abo, Goat Seep, and Capitan. Modified after Garber et al. (1989).

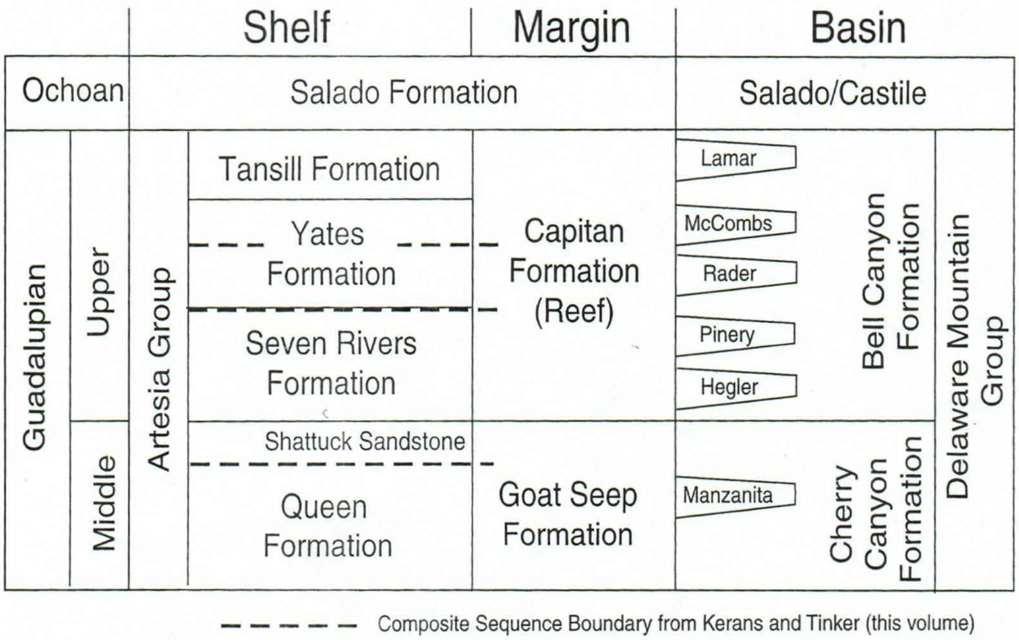

FIG. 2.—Stratigraphic nomenclature for Capitan depositional system and earlier Goat Seep margin. The Seven Rivers, Yates, and Tansill formations on the shel correlate with the Capitan Formation of the reef margin and slope, and with basin fill of the Bell Canyon Formation. Five limestone members of the Bell Canyoı Formation aré regionally recognized at the basin edge. Composite sequence boundaries of C. Kerans and S. W. Tinker (this volume) are also shown.

(1957), Payne (1976), Bozanich (1979), Broadhead (1993b), Borer and Harris (1995), Basham (1996), and many others.

INTERPRETATION OF SUBSURFACE DATA

The foundation of this paper is a reprocessed seismic line that images the Capitan depositional system much better than previously published seismic lines. A better understanding of stratal geometries from this seismic data led to improved correlations between wells with wireline logs. Our wireline log cross-section also includes porosity logs that were not presented in previously published subsurface cross-sections in Garber et al. (1989). Fig. 1 shows the location of the seismic line and wells in cross-sections relative to the outcrops in the Guadalupe Mountains.

Seismic Data

Although seismic data lack the resolution of large-scale canyon outcrops in the Guadalupe Mountains, some large-scale correlations between the shelf and basin can be better understood with the seismic data because the seismic data contain the entire stratigraphic section. In contrast, all outcrop sections have either substantial amounts of the Capitan and depositionally equivalent strata eroded from the top of the section or covered below the outcrop section. The seismic line shown in Figs. 3 and 4 is a 1991, 160-fold Vibroseis high resolution line with an orientation almost perpendicular to depositional strike. Data were acquired from 6–125 Hz, and a time invariant filter of 8–90 Hz was used during processing. Fig. 3 (top) shows an uninterpreted line with little vertical exaggeration; whereas Fig. 3 (bottom) is a lightly annotated version of the same line that is hung stratigraphically from the base of the Salado Formation. Fig. 4 shows the same line in uninterpreted (top) and interpreted (bottom) versions, again flattened on the base of the Salado Formation, but the line has an expanded vertical scale.

The seismic data (Fig. 4) show many stratigraphic characteristics of the Capitan depositional system, including (1) a massive prograding reef/slope, (2) back-reef/shelf interior reflectors that dip and diverge basinward before disappearing into the

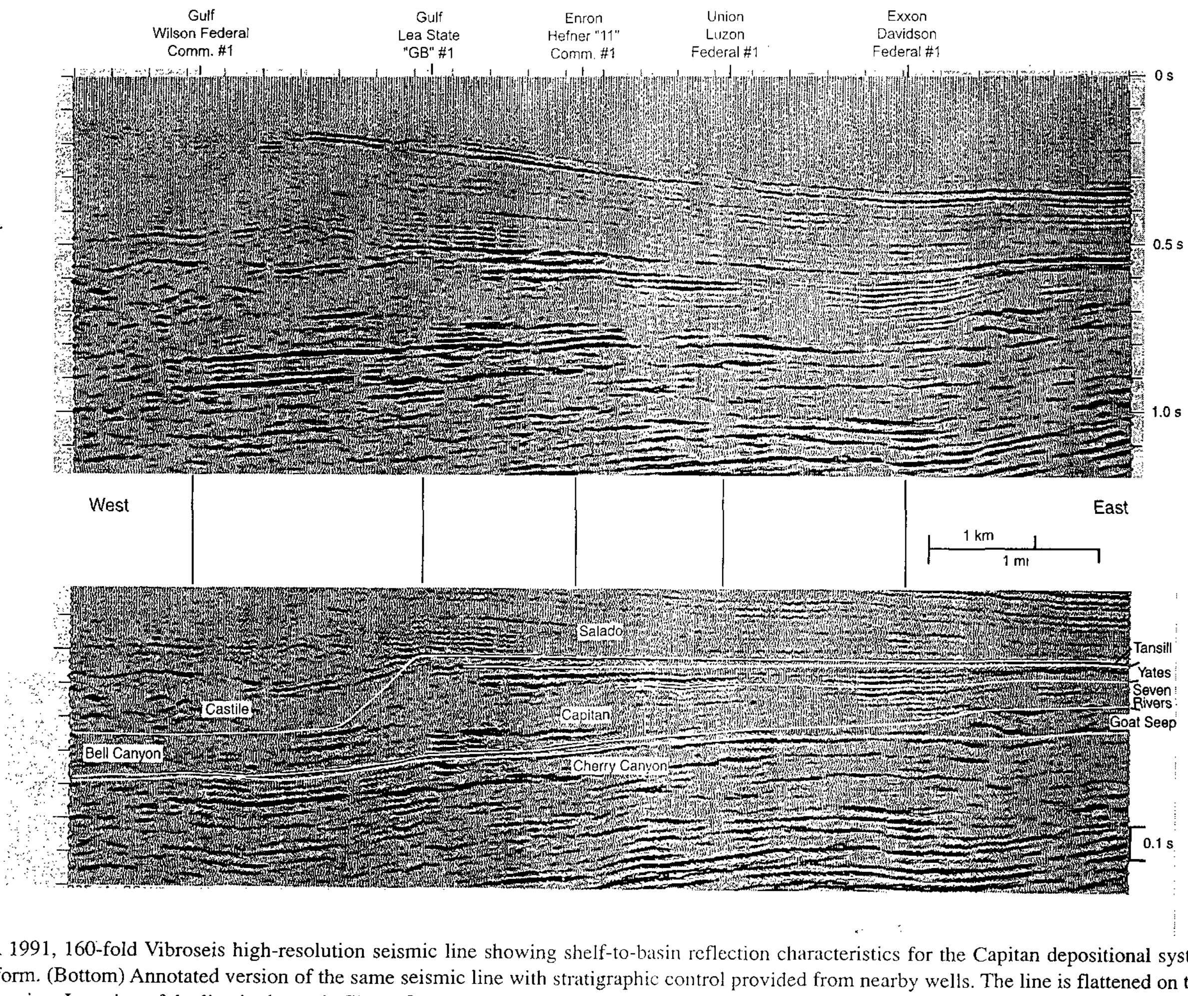

FIG. 3.—A 1991, 160-fold Vibroseis high-resolution seismic line showing shelf-to-basin reflection characteristics for the Capitan depositional system. (Top) Uninterpreted form. (Bottom) Annotated version of the same seismic line with stratigraphic control provided from nearby wells. The line is flattened on the base of the Salado Formation. Location of the line is shown in Fig. 1. Positions of wells are extrapolated onto the seismic line. None of the wells actually occur on the seismic line (see Fig. 1). The vertical scale is two-way-travel time. At these scales, the horizontal scale is similar to the vertical scale (little vertical exaggeration). Seismic data were provided by Seismic Exchange, Inc.; annotation is that of the authors. Data were used with the permission of Chevron North America Production Company.

massive reef, and (3) layered bottomset beds that thicken basinward through the addition of younger beds. The massive Capitan reef/slope seismic facies is bounded on the up-dip (east) end by shelf reflectors and on the down-dip (west) end by the lower slope reflectors. The long-term progradational history of the seismic facies that equates with the reef/slope is quite evident in Fig. 4. Greater than 3 mi (5 km) of basinward progradation is apparent for the reef/slope facies in this area. Back-reef/shelf interior reflectors indicate that shelf strata dip and also prograde basinward.

Comparison of the synthetic seismogram shown in Fig. 5 with the log response shown in Figs. 6 and 7 indicates that reflectors in back-reef/shelf interior strata are caused largely by acoustic impedence contrasts associated with interbedded sandstones and carbonates. In contrast, the lack of strong reflectors in the reef/slope (Figs. 4 and 5) indicates a lack of density or velocity changes related to interbedded sandstones or other lithologic variations of sufficient thickness to produce a contrast in acoustic impedence. The reef/slope generally lacks reflectors indicative of bedding or timelines. Many of the vague seismic reflectors present in the reef/slope interval in Fig. 4 (bottom) are thought to be the result of multiples.

Distinct reflection patterns are present in the lower slope and basin beds (Fig. 4 bottom, 5). In general, those reflections are nearly parallel to the top of the Tansill and are the result of interbedded slope carbonates and onlapping basinal sandstones. The number of slope to basin reflectors of Capitan age increase in a basinward direction with reflectors being added to the upper part of the section. Figs. 6 and 7 show that this situation apparently is due to the addition of younger basin sandstone and carbonate beds in more basinward locations during progradation.

Well Log Cross-section

Wireline logs, principally gamma ray, acoustic, and neutron porosity, indicate features of lithologic and stratigraphic importance to the Capitan depositional system (Fig. 6). Three main lithologies (carbonates, sandstones/siltstones, and evaporites) are present locally in the subsurface and can be identified from modern wireline logs; no cuttings or core samples were examined from wells shown in Fig. 6. Permian sandstones in the Delaware basin are generally feldspathic, and hence give off

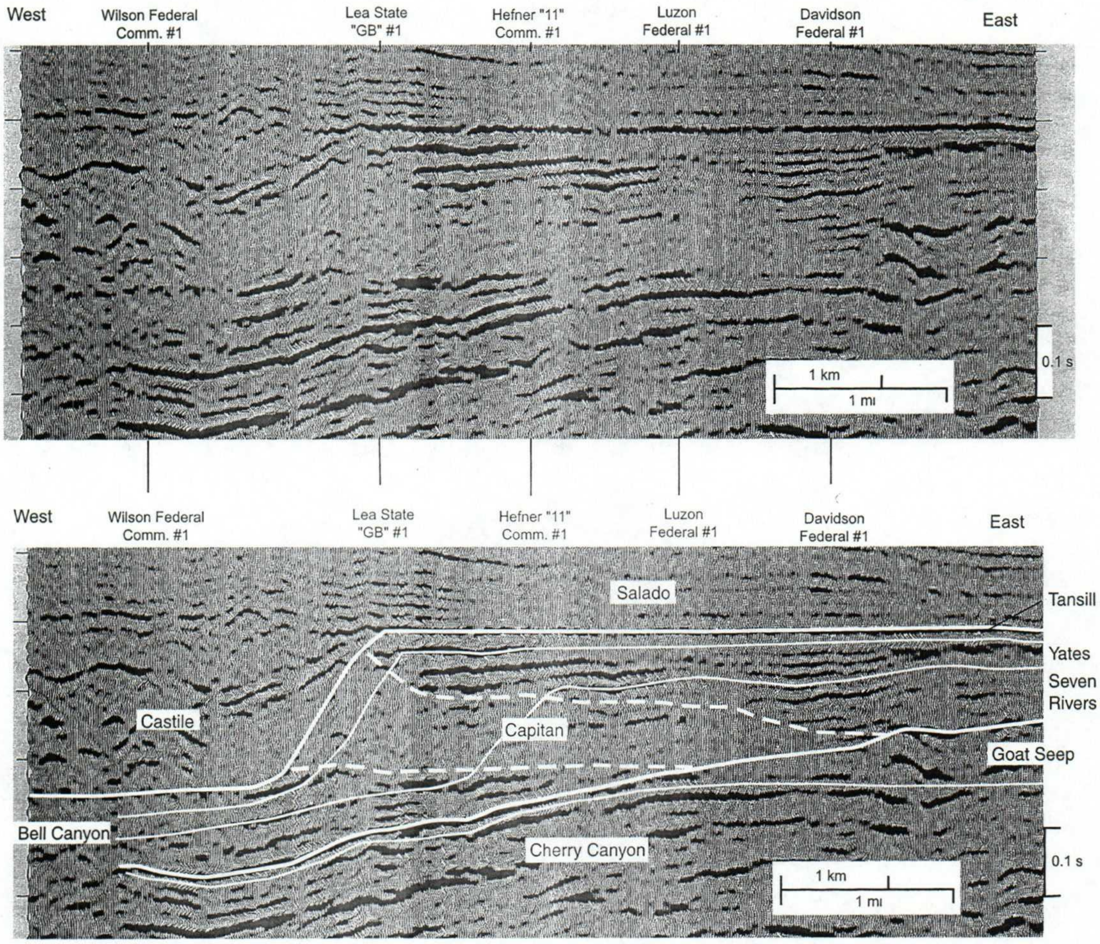

FIG. 4.—Uninterpreted (top) and interpreted (bottom) seismic line of the Capitan depositional system with vertical scale enlarged from Fig. 3. See Fig. 6 for details of well data. Fig. 1 shows location of seismic and well data. Note that positions of wells are extrapolated onto the seismic lines, and none actually occur on the line. The line is flattened on the base of the Salado Formation. The vertical scale is two-way-travel time. The vertical exaggeration is approximately 2:1, although it varies with the velocity of the strata. Seismic data were provided by Seismic Exchange, Inc.; interpretation is that of the authors. Data were used with the permission of Chevron North America Production Company.

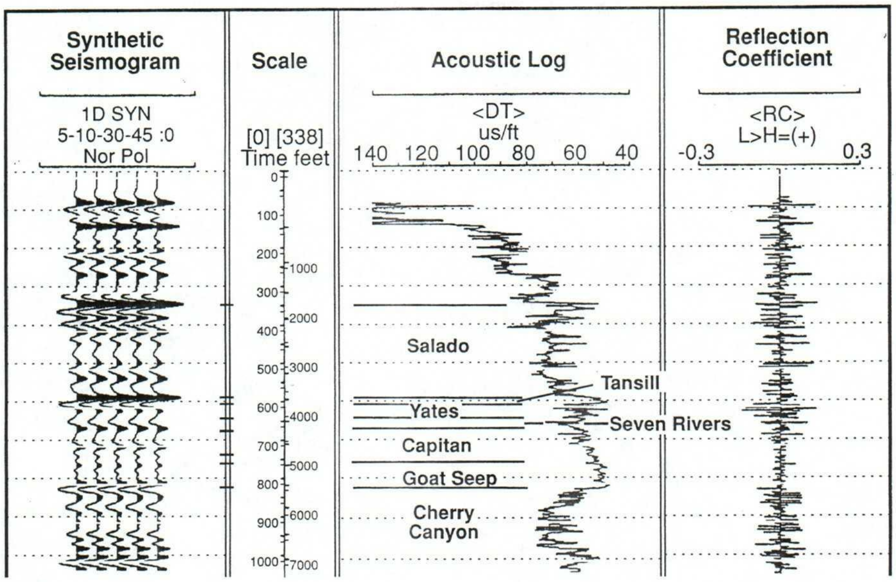

FIG. 5.—Synthetic seismogram for Humble Oil and Refining (Exxon) Davidson-Federal No. 1 well showing the relationship between acoustic log, seismic reflections, and stratigraphy of the Capitan depositional system.

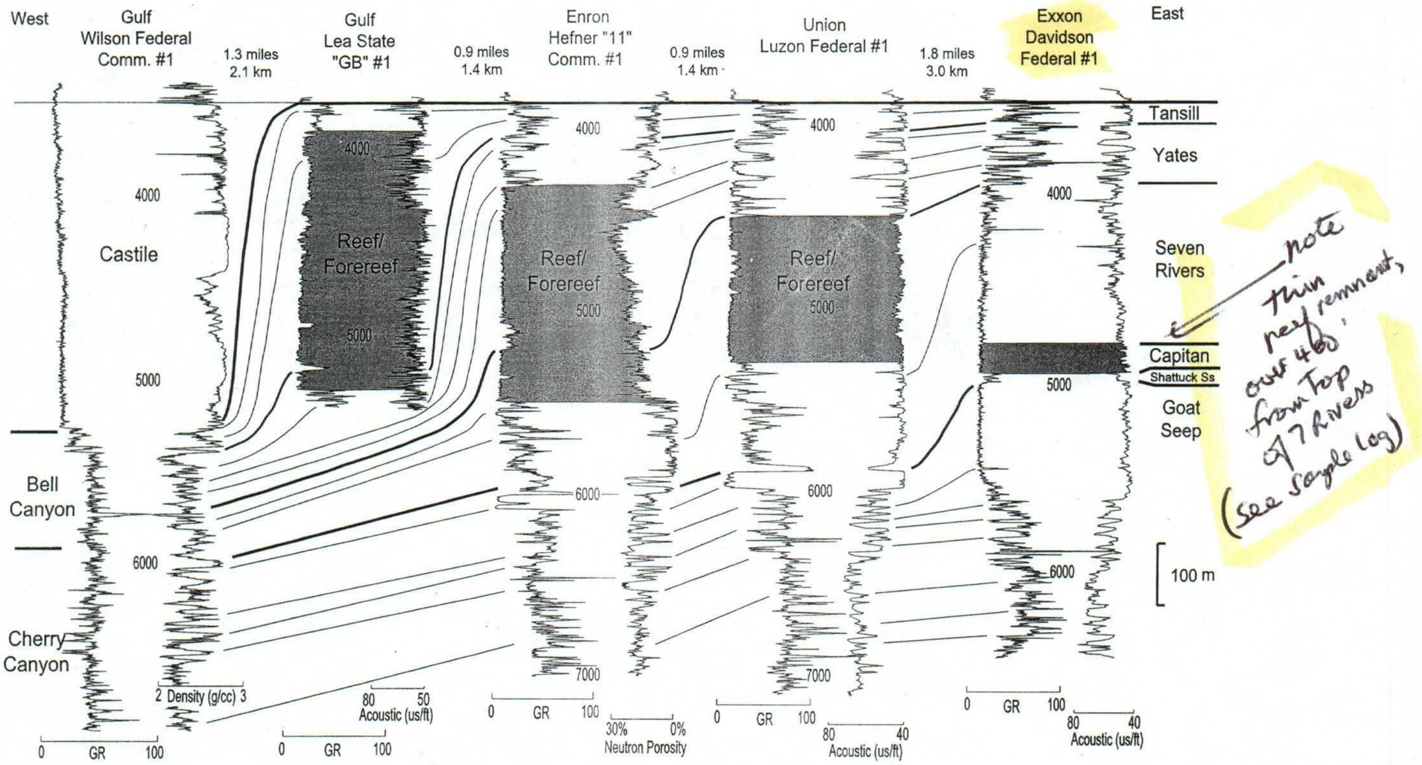

FIG. 6.—Wireline log cross-section using wells located near the seismic line shown in Figs. 3 and 4. Stratigraphy and shelf-to-basin correlations for the Capitan depositional system are shown. Section is approximately dip-oriented. Correlations follow seismic geometries as well as log patterns. Section is stratigraphic; datum is top Tansill Formation except for basin well where top Castile is used. Well locations are shown in Fig. 1.

substantial gamma-ray radiation. In contrast, strata with low gamma-ray radiation are generally carbonates or evaporites. Carbonates are mainly limestone and dolomite, and evaporites include anhydrite and halite. On wireline logs, distinctly higher density and acoustic velocity distinguish anhydrite from carbonate and halite, whereas distinctly lower density and acoustic velocity distinguish halite from carbonate. Some carbonates have substantial gamma-ray response due to uranium enrichment; these radioactive carbonates are generally not porous due to pervasive cementation (Garber et al., 1990) and hence can be differentiated from sandstones by their higher density and/or acoustic velocity.

The steepness of the Capitan shelf margin and great difference in paleodepth between shelf and basin complicate well-to-

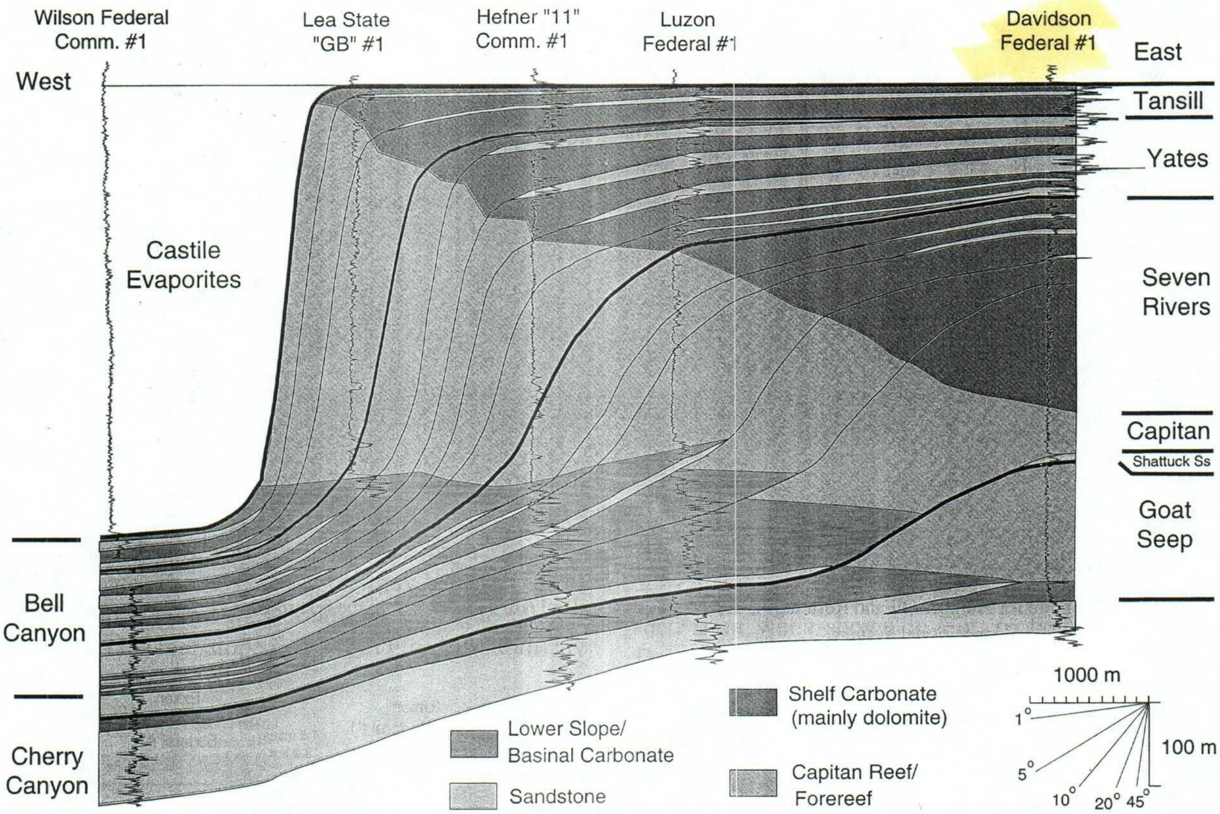

FIG. 7.—Stratigraphic cross-section of the Capitan depositional system showing gamma-ray logs, subsurface stratigraphy, lithologies and depositional environments interpreted for wells in Fig. 6.

well correlations. A wireline log cross-section of wells in the vicinity of the seismic line (Fig. 6) illustrates the stratigraphy of the shelf-to-basin profile of the Capitan depositional system in more detail than possible from the seismic data alone. The correlations shown in Figs. 6 and 7 are guided by the stratal geometries interpreted in Fig. 4 (bottom) and from the dip of the Capitan reef/slope on outcrops. Dip of the Capitan reef/slope is commonly 20° to >45°, as seen in McKittrick Canyon (Bebout and Kerans, 1993; Tinker, 1996, 1998). Equally steep dips are indicated by the seismic correlations shown in Fig. 4 (bottom); dips of the Capitan reef/slope steepen and height of the margin increases from Seven Rivers to Tansill times. Although the well-to-seismic ties for Fig. 4 (bottom) are not exact, they are close enough that the well log correlations between the shelf and basin in Fig. 6 are those suggested by the seismic data.

Seismic reflectors in the Seven Rivers, Yates, and Tansill formations clearly show basinward divergence, and hence back-reef sands should be correlated accordingly (Fig. 7). As a result, the Yates time-stratigraphic unit thickens basinward from 104 m (340 ft) in the Davidson well to 143 m (470 ft) in the Luzon well before merging into the Capitan reef (Figs. 6 and 7). The Tansill displays a similar basinward thickening from 40 m (130 ft) in the Davidson well to 50 m (165 ft) in the Luzon well and 61 m (200 ft) in the Hefner well. If only wireline logs were available, then one might (incorrectly) correlate back-reef sandstones parallel to the top of the Tansill.

Distinct lithologic patterns are apparent in subsurface shelf strata. Sandstones are most abundant in the Yates Formation, where they constitute approximately half the section in shelfward wells such as the Davidson (Fig. 7). Sandstone beds range in thickness from <1 m (3 ft) to approximately 15 m (50 ft), with several sandstones in the Hefner, Luzon, and Davidson wells that are approximately 10 m (30 ft) thick (Fig. 7). In the Yates interval, shelf sandstones decrease in number and thickness basinward and eventually pinch out behind the reef as carbonates increase. Sandstones are less abundant in the Seven Rivers Formation due in part to the basinward location of our wells. Sandstones are rare and thin in the subsurface Tansill Formation.

Although interbedded with sandstones, shelf carbonates contain little sand, as indicated by gamma-ray logs (Fig. 6). Porosity logs (acoustic, density, neutron) indicate that most of the carbonate has low porosity, though some more basinward shelf carbonates have porosity >5%. Shelf interior strata of the Tansill Formation are characterized by substantial gamma-ray radiation, high density, and high acoustic velocity, which suggests that the Tansill in these wells is similar to the dense carbonate with evaporites described by Garber et al. (1989) from the PDB-04 cores. It is not clear where the radioactive elements producing the gamma-ray response occur, but it may be in magnesite, as shown by Garber et al. (1990).

Gamma-ray response is not uniform throughout the reef-dominated section in all wells. Siliciclastic-rich intervals are indicated within reef section equivalent to the basal Yates in the Hefner well, in the reef equivalent to the upper Seven Rivers in the Luzon well, and at the Capitan–Goat Seep boundary, that is, the Shattuck Sandstone, in the Davidson well. These carbonate-clastic alternations may be responsible for some of the low-amplitude, discontinuous reflectors that are evident within the Capitan reef as interpreted in Fig. 4 (bottom). The siliciclastics are thin and laterally discontinuous enough, however, that significant amplitude variations and continuous seismic reflectors generally do not occur. The boundary between the Capitan and Goat Seep reefs does not coincide with a strong seismic reflector (Fig. 5), even though the boundary is marked by the prominent Shattuck Sandstone on outcrop and its likely equivalent between 4900–5000 ft (1500–1525 m) in the Davidson well (Figs. 6 and 7).

Fig. 7 also shows that additional (higher) sandstone beds occur on the slope and basin edge immediately basinward of where shelf sandstones pinch-out against the reef. This observation supports the idea that sandstones in the basin and shelf occur immediately above the same stratigraphic boundary and is consistent with the depositional model shown in Fig. 8.

DISCUSSION OF SUBSURFACE AND OUTCROP DATA

Depositional Model

The stratigraphic and depositional framework interpreted for the subsurface Capitan system (Figs. 4, bottom, and 7) is generally consistent with models proposed from outcrop equivalents (Smith, 1974; Borer and Harris, 1995; Tinker, 1996, 1998; Osleger, 1998; D. A. Osleger and S. W. Tinker, in press, 1999; Kerans and Tinker, this volume). These models follow the concepts of Meissner (1972), Mazzullo et al. (1985), and Fischer and Sarnthein (1988) regarding the relationship between shelf and basin strata. During highstands, the shelf was flooded and carbonates were deposited on the outer 10–20 km (6–12 mi) of the shelf as well as the shelf margin and slope (Fig. 8, top). Down-slope carbonate debris beds accumulated repeatedly (Garber et al., 1989; Brown and Loucks, 1993 a, b). The shelf margin and slope prograded basinward as the shelf aggraded during highstands. During sea-level fall, the shelf was apparently subaerially exposed, allowing sands and silts to be transported across the shelf and into the basin (Fig. 8, middle). Carbonate debris beds generated during lowstand conditions contain a siliciclastic matrix (Garber et al., 1989). The relative lack of sand in the reef and upper slope (Figs. 6 and 7) indicates that they were generally bypass zones during times of low sea level. Though the reef and upper slope remained subtidal during base-level fall, they were too steep to accumulate significant amounts of siliciclastic material. Some sand did fill internal cavities, vugs, and fracture porosity in the reef (Garber et al., 1989; Kirkland et al., 1993), and minor amounts of sandstone/siltstone occur on the upper slope (Mruk and Bebout, 1993). Although depositional models for the basinal sandstones are still being debated (Hill, 1996), several studies, e.g. Borer and Harris (1995), suggest that the time of maximum siliciclastic deposition in the basin was during lowstands. Sand was not trapped on the shelf until the subsequent transgression, when the shelf was reflooded (Fig. 8, bottom) (e.g., Fischer and Sarnthein, 1988; Borer and Harris, 1995; Osleger, 1998).

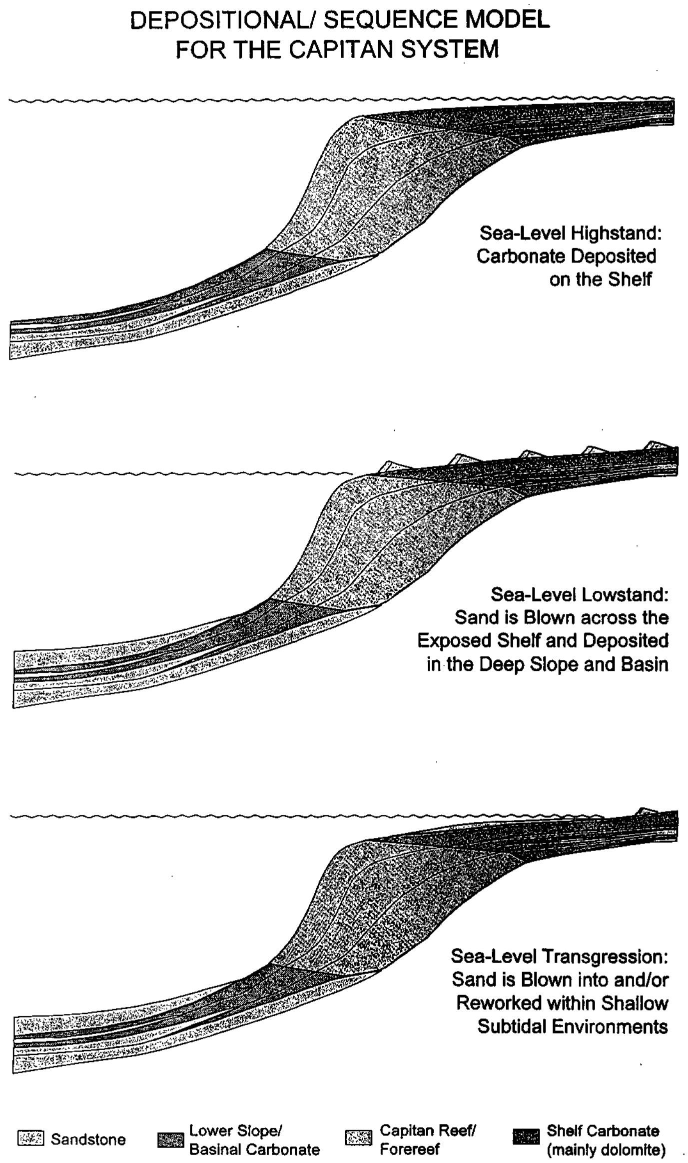

FIG. 8.—Simplified model applicable to the Capitan depositional system. The model is based on concepts of Meissner (1972), Borer and Harris (1995), Rankey and Lehrmann (1996), and Osleger (1998) that stress changes related to fluctuations in sea level and related shelf, shelf margin, and basin stratigraphy.

Shelf cycles produced by deposition portrayed in Fig. 8 are generally asymmetric regressive hemicycles that vary systematically across the shelf and within the context of smaller-scale sequences. Kerans and Harris (1993), Rankey and Lehrmann (1996), Tinker (1996, 1998), Osleger (1998), and D. A. Osleger and S. W. Tinker (in press, 1999) examined the lateral variation and stacking patterns of cycles outcropping in McKittrick and Slaughter canyons. Their work shows that there is substantial variation in the nature of a cycle depending on its position along the depositional profile and within a sequence. A good indication of this lateral variation within a depositional cycle/sequence is shown by the changes in log character within any one of the units correlated in Fig. 6. The lateral variation is also likely responsible for changes in seismic reflectors within the shelf strata, e.g., the number and amplitude of reflectors within the Yates Formation varies laterally between the Davidson and Hefner wells in Fig. 4 (bottom).

Sequence Stratigraphy

Recent analysis of the Permian in the Guadalupe Mountains has emphasized the application of sequence stratigraphic concepts and the analysis of high-frequency (Milankovitch-band) cyclicity to guide facies analysis and refine shelf-to-basin correlation (Sarg and Lehmann, 1986; Sonnenfeld, 1991; Kerans et al., 1992, 1993, 1994; Kerans and Fitchen, 1995). Only recently have the studies of Kerans and Harris (1993), Borer and Harris (1995), Rankey and Lehrmann (1996), Tinker (1996, 1998), Osleger (1998), D. A. Osleger and S. W. Tinker (in press, 1999), and C. Kerans and S. W. Tinker (this volume) begun to place the Capitan depositional system into a high-resolution stratigraphic context. Meissner (1972), Kerans et al. (1992, 1993), Borer and Harris (1995), and C. Kerans and S. W. Tinker (this volume) extrapolated shelf cycles and sequences to the time-equivalent basin deposits of the Bell Canyon Formation. Borer and Harris (1995) suggested that siliciclastics bypassed the shelf and were delivered to the basin during high-frequency lowstands of sea level during deposition of the Yates Formation. The record of high-frequency bypass is also evident in slope equivalents of the youngest portion of the Yates Formation and the Tansill Formation in the McKittrick Canyon outcrops (Brown and Loucks, 1993a, b; Mruk and Bebout, 1993; Brown, 1996).

Shelf-to-basin correlations discussed in Garber et al. (1989) suggest that deposition of 50% to possibly 70% of the Bell Canyon siliciclastics occurred in the basin while a correspondingly thick sequence of very sand-poor Seven Rivers carbonates accumulated on the shelf. In contrast, Borer and Harris (1995) suggest that over 50% of the Bell Canyon Formation equates to the Yates shelf deposits. Figs. 4 (bottom) and 6 suggest that approximately 40% of the Bell Canyon siliciclastic section is equivalent to the Seven Rivers Formation, approximately 40% is equivalent to the Yates Formation, and approximately 20% is equivalent to the Tansill Formation.

Kerans and Tinker (this volume) interpret three composite sequences within the Capitan depositional system, basing their analysis on the large-scale stratigraphic framework developed for the Guadalupe Mountains by Kerans et al. (1992, 1993) and Kerans and Fitchen (1995) and the detailed work within McKittrick Canyon by Tinker (1996, 1998). Their correlations between the shelf and basin edge carbonates include Seven Rivers composite sequence to Manzanita, Hegler, and Pinery members of the Cherry Canyon and Bell Canyon formations, Yates composite sequence to Rader and McCombs members of the Bell Canyon Formation, and Tansill composite sequence to the Lamar member of the Bell Canyon Formation. The correlation of the Manzanita member of the Cherry Canyon to the lowest Seven Rivers Formation remains controversial and is not supported by our subsurface data; however, our correlations in the basin are equivocal and hampered because the basin-margin carbonate members of the Bell Canyon Formation could not be picked in the Wilson well with any certainty. The Tansill/Yates sequence boundary of Tinker (1998) and Kerans and Tinker (this volume) is below the traditional subsurface and outcrop pick for the Yates and Tansill formations (King, 1948; Newell et al., 1953; Hayes, 1964; Garber et al., 1989). Our Tansill-Yates boundary is picked higher than the sequence boundary of Kerans and Tinker (this volume), but is approximately at the traditional subsurface pick for the boundary as shown by Garber et al. (1989).

Progradation of the Capitan

Maximum progradation of the Capitan shelf margin occurred in the north-central portion of the Delaware basin, with substantially less progradation in the northeastern and northwestern portions of the Delaware basin (Silver and Todd, 1969; cross-sections by West Texas and Roswell Geological Societies; Garber et al., 1989). Fig. 1 illustrates the variable amount of progradation by comparing the position of the youngest Goat Seep margin, which is essentially the starting point for Capitan reef growth, with the position of the youngest Capitan reef margin during Tansill time. Figs. 4 (bottom) and 7 indicate approximately 5 km (3 mi) of Capitan reef margin progradation in the northeastern Delaware basin with slightly over half of the progradation occurring below the first Yates sandstone, or during Seven Rivers time. The model of Garber et al. (1989) also indicates maximum progradation during Seven Rivers time. This pattern is similar to that recognized in McKittrick Canyon outcrops from the northwestern portion of the basin. Tinker (1996, 1998) shows approximately 3 km (1.8 mi) of progradation during Seven Rivers deposition in McKittrick Canyon. The reconstruction of eroded Yates and Tansill strata in McKittrick Canyon by Bebout et al. (1993), Borer and Harris (1995), and Tinker (1996, 1998) shows approximately 2 km (1.2 mi) of additional progradation, for a total of approximately 5 km (3 mi) of Capitan progradation. Less progradation occurred during Yates and Tansill time as the margin steepened such that slopes into the basin approached 30° (King, 1948), and water depths increased in the basin to over 600 m (> 2000 ft) in Tansill time. These relationships are also supported by correlations shown in Fig. 4 (bottom).

Recent outcrop studies (e.g., Kerans and Harris, 1993; Tinker, 1996, 1998; Osleger, 1998; D. A. Osleger and S. W. Tinker, in press, 1999) focus on trends in down-dip thickness changes, lateral extent and aspect ratios of facies tracts, progradation:aggradation ratios, and derived offlap angles to better document the details of outer-shelf and margin progradation. The outcrop studies of Tinker (1966, 1998) and the computer modeling of Borer and Harris (1995) show how progradation is expressed by the episodic but progressive seaward step-out of the shelf margin within individual small-scale sequences. This same step-out style of progradation is apparent in Figure 4 (bottom), but because of less seismic resolution, the nature of the progradation shown in Figs. 4 (bottom) and 7 does not have the same detail as outcrop studies.

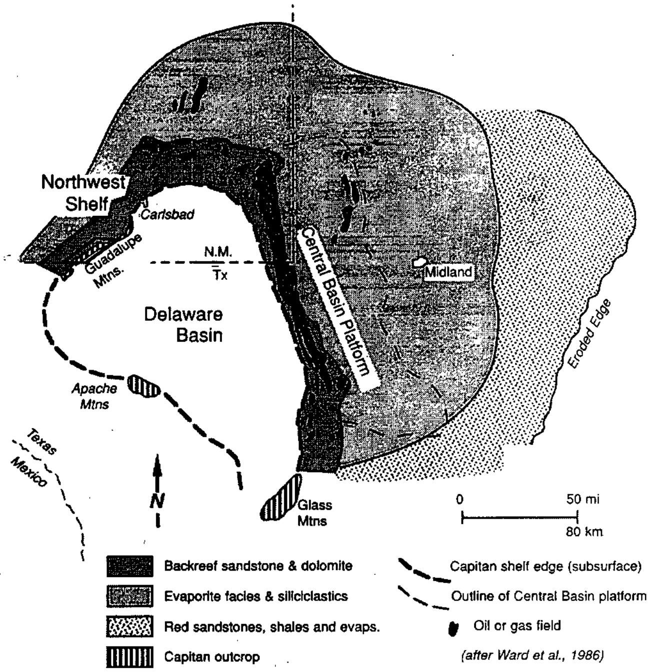

FIG. 9.—Simplified geologic map of depositional environments inferred for Capitan time, which shows the location of hydrocarbon production from shelf reservoirs (modified from Ward et al., 1986). See Table 1 for information on some of the fields.

Basinward Thickening of Shelf Strata

The subsurface correlations of shelf strata (Figs. 6 and 7) show a basinward thickening that is consistent with the more detailed outcrop correlations of Tyrrell (1969), Yurewicz (1977), Hurley (1978, 1989), Borer and Harris (1991a), Longley and Harwood (1992), Kerans and Harris (1993), Tinker (1996, 1998), Osleger (1998), D. A. Osleger and S. W. Tinker (in press, 1999), and C. Kerans and S. W. Tinker (this volume). All of these studies show a basinward thickening and increase in dip of shelf (back-reef) strata into the Capitan reef. King (1948) and Newell et al. (1953) recognized the basinward tilting of outer-shelf deposits, and Pray informally designated these inclined beds as "fall-in" beds (Pray and Esteban, 1977). If the Seven Rivers, Yates, and Tansill formations are defined as time stratigraphic units, then they should also thicken toward the reef. If instead these formations are defined by lithology (that is, Yates Formation is interbedded sand and carbonate), then back-reef formations may have more tabular geometries, as shown by Toomey and Babcock (1983) and Garber et al. (1989). However, those formation boundaries will then cut across timelines.

Thick accumulations of outer-shelf facies accentuate the basinward progradation that occurs within successive small-scale sequences (Tinker, 1996, 1998; Osleger, 1998; D. A. Osleger and S. W. Tinker, in press, 1999). Studies by Yurewicz (1977), Hurley (1978, 1989), and Longley and Harwood (1992) indicated that the basinward dip of the outer-shelf beds could be due to either primary depositional dip or synsedimentary differential subsidence, but not tectonic deformation as thought by Newell et al. (1953) and Kelley (1972). Borer and Harris (1995) interpreted the shift in the locus of sedimentation to be a response to base-level fall along small-scale sequence boundaries, where the abrupt expansion in thickness in each sequence occurs directly above the reef margin of the preceding sequence. Syndepositional differential compaction of slope and basinal strata is interpreted to have generated substantial accommodation space on the prograding Capitan shelf margin (Hunt et al., 1995; Saller, 1996; A. Longley, this volume); however, Osleger (1998) indicates that not all seaward thickening within the Yates sequences can be attributed to compaction. The basinward thickening of shallow shelf and peritidal strata of the Yates and Tansill formations (Figs. 4, 6, and 7) supports basinward tilting and accommodation due to differential compaction of underlying slope and basinal strata.

Evaporites

An important mineralogical difference between outcrops and subsurface equivalents of the Capitan depositional system is the small amount of evaporites in the outcrops. Anhydrite and gypsum are common as interbeds, nodules, and cements in back-reef/shelf interior sandstones and dolomites of the subsurface (Crawford and Dunham, 1982; Ordonez, 1984; Garber et al., 1989; Borer and Harris, 1991a, b; Andreason, 1992), however they are very rare in similar facies in outcrops. In many cases, the anhydrite/gypsum originally present in outcropping strata has simply been dissolved; hence porosity apparent on outcrop may not be representative of the subsurface. In some cases, like that of the Capitan Formation, anhydrite may have, in part, been altered to calcite (Scholle et al., 1992). Evaporites play a major role in the subsurface in trapping of hydrocarbons in shelf reservoirs of the Capitan depositional system.

HYDROCARBON DISTRIBUTION

Porosity in the Capitan depositional system is closely related to facies. The subsurface Capitan reef/slope that rims the Delaware basin has moderate porosity and high permeability. Shelf sandstones and some shelf carbonates (especially grainstones) adjacent to the reef have good porosity and moderate permeability, but porosity and permeability in those beds generally decrease lagoonward, away from the reef margin. Basin carbonate beds are generally not porous, but some basin sandstones in elongate channels have good porosity and moderate permeability.

The upper 122 m (402 ft) of Capitan reef in the PDB-04 well has porosity of 5–25% (average 10%) and permeability of up to 2 darcies (average 256 mD), whereas the lower Capitan is less porous (less than 5%) and permeable (less than 1 mD) (Garber et al., 1989). Wireline logs of Fig. 6 also show that the Capitan reef (especially the upper portion) has substantial porosity (>5%), and hydrologic data (Motts, 1968; Hill, 1996) indicate that the reef has excellent permeability regionally. Although porous and permeable, hydrocarbons do not occur in the Capitan reef because the reef does not have structural or stratigraphic closure. Hydrocarbons migrating out of the Delaware basin apparently moved through the Capitan reef/slope and into permeable shelf deposits up-dip from the reef (Ward et al., 1986). The Capitan Formation is a high permeability, fresh water aquifer around the margins of the basin.

Hydrocarbon reservoirs are present in shelf and basin equivalents to the Capitan Formation (Galloway et al., 1983; Ward et al., 1986; Broadhead, 1993a, b). Hydrocarbon production from shelf portions of the Capitan depositional system generally occurs in stratigraphic and combination stratigraphic-structural traps (Fig. 9; Galloway et al., 1983; Ward et al., 1986; Broadhead, 1993a). Individual siliciclastic reservoir zones show complex interfingering with carbonates in a down-dip direction and evaporites in an up-dip direction (Borer and Harris, 1991a). In addition to these stratigraphic traps caused by facies changes and evaporite cementation, low-relief anticlines caused by compaction and draping over buried structures serve as structural traps (Ward et al., 1986).

Hydrocarbon production on the shelf is primarily from sandstone beds of the Yates and Seven Rivers formations, with minor production from dolomites (Table 1; Galloway et al., 1983; Ward et al., 1986; Borer and Harris, 1991a, b). The most widespread porosity and hydrocarbon reservoirs occur in relatively well-sorted sandstones. Reservoir-grade sandstones have porosities of 15% to 30% and permeabilities of 10 mD to 100 mD (Borer and Harris, 1991a, b). Some porosity also occurs in carbonate beds, especially grainstones in the upper part of beds near the reef (Ordonez, 1984). Porosity in carbonates deteriorates toward the platform interior. The evaporites always have low porosity and permeability.

Many fields along the northern margin of the Delaware basin produce oil from either the Seven Rivers or Yates formation, but not both. In contrast, fields along the western edge of the Central Basin platform produce from stacked reservoirs in both the Seven Rivers and Yates formations (Fig. 9; Ward et al., 1986). The Queen, Seven Rivers, and Yates formations produce with only minor breaks for approximately 145 km along strike along the western edge of the Central Basin platform (Ward et al., 1986). The official field boundaries are generally industrial and not geological. Five fields along this trend have produced over 100 million barrels (Mbbl) of oil, with the North Ward-Estes field (Ward and Winkler Counties, Texas) being the largest, with cumulative production exceeding 350 million barrels (Mbbl) of oil (Table 1). The Tansill Formation produces erratically along the Northwestern shelf and the western edge of the Central Basin platform from small fields in back-reef dolomites (Ordonez, 1984).

A number of small oil fields occur in basin sandstones that were deposited during Capitan time (Galloway et al., 1983; Ward et al., 1986; Williamson, 1977; Broadhead, 1993b). Cumulative production from these fields is generally small, less than 30 million barrels of oil (Table 2). The fields tend to be very elongate (1.5–19 km long by <1–6 km wide; 0.9–11 mi long by <0.6–3.6 mi wide), apparently reflecting accumulation of reservoir sands in deep-water channels (Bozanich, 1979;

TABLE 1.—SOME HYDROCARBON FIELDS PRODUCING FROM CAPITAN SHELF EQUIVALENTS

Name	County-State	Discovery Date	Depth (ft)	Type	Cum. Prod. (million barrels or billion cubic feet)*	Reservoir (Lithology)	Trap Type
Eumont	Lea, NM		5000	Oil	69.100	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Eumont	Lea, NM		4000	Gas	1,451.865	Yates-Seven Rivers-Queen (Ss-St)	Strat (evaporites updip)
Eunice	Lea, NM	1930	5000	Oil	28.409	Seven Rivers-Queen (Ss-St)	Strat (evaporites updip)
GMK S.	Gaines, TX	1957	5598	Gas	15.806	Yates (Ss-St)	Strat
Halley	Winkler, TX	1939	3150	Oil	17.695	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Hendrick	Winkler, TX	1926	3100	Oil	257.685	Yates-Seven Rivers (Ss-St, Dol)	Strat (evaporites updip)
Homann	Gaines, TX	1977	5328	Gas	9.320	Yates (Ss-St)	Strat
Jalmat	Lea, NM		5000	Oil	64.264	Tansill-Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Jalmat	Lea, NM		4000	Gas	1,640.896	Tansill-Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Kermit	Winkler, TX	1928	2800	Oil	105.576	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Rhodes	Lea, NM	1927	5000	Oil	11.116	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Rhodes	Lea, NM	1927	5000	Gas	197.237	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Scharbrough	Lea, NM	1965	3200	Oil	16.236	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Scharbrough	Winkler, TX**	1927	3200	Oil	27.062	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Seminole	Gaines, TX	1936	5032	Gas	22.085	Yates (Ss-St)	Strat
Shafter Lake	Andrews, TX	1952	3054	Gas	25.067	Yates (Ss-St)	Strat
Ward-Estes N.	Ward/Winkler, TX	1929	3000	Oil	347.958	Yates-Seven Rivers-Queen (Ss-St)	Strat (evaporites updip)
Ward S.	Ward, TX	1938	2700	Oil	101.434	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Wilson	Lea, NM	1928	5000	Oil	9.045	Yates-Seven Rivers (Ss-St)	Strat (evaporites updip)
Shugart	Eddy, NM	1937	2656	Oil	20.179	Yates-Seven Rivers-Queen	Strat

*As of 1984

**Eaves and Leck fields also included

TABLE 2.—SOME HYDROCARBON FIELDS PRODUCING FROM CAPITAN BASINAL EQUIVALENTS

Name	County-State	Discovery Date	Depth (ft)	Type	Cum. Prod. (million barrels or billion cubic feet)*	Reservoir (Lithology)	Trap Type
El Mar	Loving, TX	1959	4532	Oil	17.374	Bell Canyon (Ss-St)	Strat
Grice	Loving, TX	1956	4510	Oil	8.433	Bell Canyon (Ss-St)	Strat
Poquito	Ward, TX			Gas	19.392	Bell Canyon (Ss-St)	Struc
Two Freds	Reeves, Ward, and Loving, TX	1957	4895	Oil	11.290	Bell Canyon (Ss)	Strat
Wheat	Loving, TX	1925	4300	Oil	21.218	Bell Canyon (Ss)	Strat
El Mar	Loving, TX	1959	4532	Oil	17.374	Bell Canyon (Ss-St)	Strat
Geraldine	Culberson & Reeves, TX	1982	3454	Oil	25.043	Bell Canyon (Ss-St)	Strat
Mason N.	Loving, TX	1952	4055	Oil	6.244	Bell Canyon (Ss-St)	Strat
Paduca	Lea, NM	1961	4000	Oil	12.846	Bell Canyon (Ss-St)	Strat
Tunstill	Reeves, TX	1947	3270	Oil	10.615	Bell Canyon (Ss-St)	Strat

*As of 1984

Williamson, 1977; Bashman, 1996). Average porosity and permeability in three Bell Canyon fields were estimated at 24–25% and 10–80 mD, respectively, by Payne (1976). Basin carbonates that are interbedded with sandstones in the Bell Canyon Formation are generally not porous.

CONCLUSIONS

Improved seismic imaging and integrated well data illustrate the similarity of the subsurface Capitan depositional system to outcrops in the Guadalupe Mountains. Shelf strata thicken basinward approaching the reef and shelf sandstones pinchout before they reach the reef. Massive reef/slope facies prograde basinward with complex step-out patterns. Slope carbonates thin and basinal siliciclastics thicken toward the basin. Although the Capitan reef has good reservoir properties, it is not in a stratigraphic and/or structural position that allows for the trapping of hydrocarbons. Instead, large oil fields occur in sandstones and a few carbonate beds in stratigraphically equivalent back-reef (shelf) strata that pinch out up-dip into impermeable sandstones/siltstones, carbonates, and evaporites of the platform interior. Smaller oil fields also occur in deep-water sandstones in the basin.

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