GUADALUPIAN (ARTESIA GROUP) AND OCHOAN SHELF SUCCESSION OF THE PERMIAN BASIN: EFFECTS OF DEPOSITION, DIAGENESIS, AND STRUCTURE ON RESERVOIR DEVELOPMENT

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ABSTRACT

The middle and upper Artesia Group (Upper Guadalupian Series) in the Permian Basin composes a section of as much as 2,650 ft (808 m) of stratigraphically cyclic, mixed siliciclastic/carbonate/evaporite platform strata that were deposited shelfward of the Guadalupian reef complex that rims the Delaware Basin. The section includes the Queen, Seven Rivers, Yates, and Tansill Formations and hosts many hydrocarbon reservoirs that are located along the margins of the Central Basin Platform in Texas and on the Northwest Shelf in southern New Mexico. As of 2003, cumulative oil production from middle and upper Artesia Group intervals exceeded 254.5 MMbbl (4.05×10^7 m^3) from more than 236 reservoirs; cumulative gas production exceeded 356,700,000 Mcf from more than 157 reservoirs. Most of the hydrocarbon production has been from siliciclastic-dominated sections in the Queen and Yates Formations, with secondary production from siliciclastics in the Seven Rivers and Tansill Formations, and from grain-dominated carbonate facies in the near back-reef area. Trapping mechanisms include basinward-dipping stratal dip, updip porosity occlusion by evaporite minerals, top seals composed of impermeable carbonate or evaporite, and local, deep-seated anticlinal structures.

Artesia facies tracts include, from basin to shelf, immediate-back-reef carbonate grainstone to packstone; shelf-crest pisolite-bearing carbonate shoals; lagoonal wackestone to mudstone and siliciclastic siltstone; algal-laminated, tidal-flat carbonate packstone to wackestone and fine- to very fine grained sandstone; beach-ridge fine sandstone; siliciclastic-sabkha anhydrite and halite; brine-pool and evaporitic-lagoon anhydritic dolomite, dolomitic anhydrite, anhydrite, and halite; and eolian to fluvial siliciclastics. During sea-level highstand, siliciclastics

are limited to updip areas, whereas eolian-siliciclastic depositional environments migrate downdip during sea-level lowstands. During transgressions, siliciclastics in more basin-proximal positions were reworked by marine and marginal processes. Reservoir quality was impacted mostly by dissolution of feldspar and carbonate allochems and precipitation of authigenic feldspar, clay, and evaporite. Overall progradation during Artesia Group deposition resulted in progressively more downdip development of reservoir facies through time.

Additional resource will be produced by infield drilling, field extension, exploitation of previously less productive or bypassed intervals, and by application of enhanced recovery techniques.

INTRODUCTION

The middle and upper parts of the Artesia Group of the Permian Basin compose a section of as much as 2,650 ft (808 m) of stratigraphically cyclic, mixed siliciclastic/carbonate/evaporite platform strata. The section hosts many economically important hydrocarbon reservoirs. Most of the hydrocarbon production has been from siliciclastic-dominated units in the Queen and Yates Formations (figs. 1, 2). More than 254.5 MMbbl of 32.12^{o} (average) oil has been produced from approximately 236 reservoirs, within which 49 percent of the 19,536 total wells were producing in 2003. The section has also produced 356,700,000 Mcf of gas from approximately 157 reservoirs, within which 63 percent of the 817 total wells were producing in 2003. Production depths range from 42 to 4,875 ft (12.8–1,485.9 m) (Railroad Commission of Texas, 2003). The Seven Rivers and Tansill Formations are also productive in some fields, often where either or both Yates and Queen are the primary producing intervals. Despite the economic significance and broad geographic distribution of several reservoir plays that contain these formations, most published technical information regarding their stratigraphy, lithology, and reservoir character is derived from only a few outcrop and field locations.

Also briefly addressed in this report are the Ochoan Series shelf intervals, which attain a maximum cumulative thickness of 3,200 ft (975m) in the Permian Basin. Ochoan strata are not prolifically hydrocarbon productive on the shelf; however, there are a few noteworthy reservoirs (Castile, Rustler) in the Delaware Basin. Ochoan strata are important to Permian Basin shelf hydrocarbon province mainly because evaporite-prone strata of the Salado Formation provide a regional top seal for Guadalupian plays. This chapter documents the depositional and diagenetic history of the Guadalupian and Ochoan shelf intervals on the basis of available data and describes the geologic controls on reservoir development, distribution, and heterogeneity.

PREVIOUS WORK

Tait and others (1962) summarized the historical development of Upper Guadalupian nomenclature in the Permian Basin. The Grayburg Formation was originally described as a subsurface unit in Eddy County, New Mexico, by Dickey (1940), extended to a surface exposure by Moran (1954), and modified somewhat by Hayes and Koogle (1958). The Queen Formation designation evolved through several iterations, including DeFord and others (1940), Woods (1940), Dickey (1940), and Moran (1954). The Seven Rivers section was defined partly by Meinzer and others (1926), described in the subsurface by Dickey (1940), and defined in the Guadalupe Mountains by Hayes and Koogle (1958). Tait and others (1962) recognized that post-San Andres Guadalupian formations in the Permian Basin (including the Palo Duro Basin) were essentially a series of genetically related intervals that possessed similar depositional components and whose similar facies tracts cyclically migrated up and down depositional slope in response to relative sea-level changes. Further, they renamed this series the *Artesia Group* because previous nomenclature (for example, Chalk Bluff Formation: Lang, 1937; Whitehorse Group: Lewis, 1938; Fritz and Fitzgerald, 1940; Davis, 1955; Bernal: Bachman, 1953) was based on imprecise or uncertain correlations, some of which were from basins outside the Permian Basin. Silver and Todd (1969) discussed the interfingering relationships between Artesia strata and the Guadalupian reef complex. However, their understanding that the Artesia Group were shelf equivalents of the Capitan-Goat Seep reef margin was shown to be technically incorrect when Fekete and others (1986) and Franseen and others (1989) demonstrated that a top-of-Grayburg unconformably underlies the Goat Seep and, therefore, the Grayburg does not interfinger with the reef complex. The controversial nature and paleobathymetry of the Capitan reef system and its position in the shelf topographic profile have been discussed by many, most notably by Lloyd (1929), Johnson (1942), Achauer (1969), Esteban and Pray (1976, 1977), Cys and others (1977), and Garber and others (1989). Other discussions of Capitan reef facies include Tyrrell (1969), Estaban and Pray (1976, 1977), Biggers (1984, 1985), and Senowbari-Daryan and Rigby (1996).

A considerable body of literature discusses the geology of the Upper Guadalupian shelf section. Particular references are provided in the following discussions of geologic aspects of the

Artesia Group. A comprehensive listing of most of the literature that discusses the geology of Artesia Group formations is provided in the references section of this chapter.

Kerans and Kempter (2002) provided the most recent and comprehensive summary of the sequence stratigraphic relationships among Artesia Group formations and between Artesia Group formations and equivalent lowstand intervals (Cherry Canyon and Bell Canyon Formations) in the Delaware Basin. Borer and Harris (1991) provided a comprehensive analysis of relative sea-level control on Yates deposition that can be applied to other Artesia Group Formations.

Comprehensive summaries of Upper Permian shelf reservoir geology and hydrocarbon plays include Galloway and others (1983), Ward and others (1986), and Dutton and others (2005). Field-scale studies of reservoir-related characteristics were discussed for the Queen by Harris and others (1984), George and Stiles (1986), Holley and Mazzullo (1988), Malicse and Mazzullo (1990), Vanderhill (1991), Holtz (1994), Harris and others (1995), Price and others (2000), and Changsu (2002); for the Seven Rivers by Bain (1994) and Kosa and others (2001); for the Yates by Casavant (1988), Borer and Harris (1991), Bain (1994), and Kosa and others (2001); and for the Tansill by Kosa and others (2001).

REGIONAL SETTING

Upper Guadalupian platform-margin units include the Goat Seep and overlying Capitan Reef trends that were located around most of the periphery of the Delaware Basin. Paleo-biota in reef facies indicates a Late Permian age (Silver and Todd, 1969; Bigger, 1984). Reef development during middle and late Guadalupian time marked a profound change in paleogeographical architecture in the Permian Basin. Previous basin margins were low-relief carbonate ramps. The Goat Seep was constructed on the eroded crest of the Grayburg carbonate ramp (Fekete and others, 1986; Franseen and others, 1989), and the Capitan Reef built up on the Goat Seep and prograded into the Delaware Basin over underpinnings of previously deposited reef talus and Delaware Mountain Group siliciclastic basinal deposits.

Much conjecture and argument have been focused on the nature of the reef system. Some writers have maintained that it resided at or near sea level (for example, Lloyd, 1929; Johnson, 1942); and even produced barrier islands (Kirkland-George, 1992), whereas others have maintained that the living reef was composed largely of algally bound silt- and sand-sized skeletal debris derived from the Northwest Shelf, contained indigenous nonframework biota (for example, sponges), and was submerged below wave base (for example, Achauer, 1969), and that the shelf crest was in a more landward position and marked by tepee structures and intertepee pisolite (for example, Esteban and Pray, 1976). Summaries of the basic models (fig. 3) for Capitan Reef development can be found in Cys and others (1977), Garber and others (1989), and Kirkland and others (1993).

The Goat Seep/Capitan reef system, a profoundly critical component of Permian Basin Guadalupian paleogeography, prominently divides the shelves of the Central Basin Platform, Northwest Shelf, and Western Shelf from the Delaware Basin. Equivalence between basin and shelf strata has long been the subject of investigation and controversy. The reef is largely massive in appearance and, although shelf strata and basin strata can be traced into their respective sides of the reef mass, none of the shelf and basin intervals can be correlated directly through the reef in outcrop or in the subsurface by using well logs. The Upper Queen Shattuck sandstone is correlated into the reef complex and is used to divide the Capitan from the older Goat Seep. However, the reef system will not be discussed in greater detail here because, although it is quite porous in many areas, it is mainly an aquifer. Only very locally (for example, Cheyenne field in Winkler County and MPF, Cutthroat, and Ft. Stockton fields in Pecos County) is the Capitan recognized as a hydrocarbon reservoir and it had cumulatively produced only 0.72 MMbbl of oil and 63,386 Mcf of gas as of 2003 (Railroad Commission of Texas, 2003).

Delaware Basin equivalents of the reef trend include the upper part of the Cherry Canyon Formation and the overlying Bell Canyon Formation (figs. 2, 4), both included in the sandstone-prone Delaware Mountain Group. The oldest Guadalupian basin unit is the Brushy Canyon Formation, which was deposited during early Guadalupian sea-level fall. The regionally widespread “pi-marker” well log interval (cored in Palo Duro Basin; Fracasso and Hovorka, 1986) may correspond to the sequence boundary (CS9/CS10 in fig. 2) between the upper and Lower San Andres Formations that marks this sea-level fall.

Shelfward of the Delaware Basin, similar cyclic facies tracts characterized each of the Goat Seep/Capitan-equivalent intervals. Nearest the shelf margin, normal-marine grain-rich carbonate facies dominated. In progressively updip positions, carbonate-depositional environments became more prone to fine-grained, biologically and circulation-restricted intertidal, supratidal, and lagoon carbonate production. Farther updip, evaporite-depositional environments and, most upslope, siliciclastic-depositional environments prevailed. Siliciclastic abundance and texture depended somewhat on proximity of source areas; however, some intervals (Yates and Queen) contain much more siliciclastic sediment than others, and other potential controls on siliciclastic influx must be addressed. Upper Guadalupian shelf equivalents include, from oldest to youngest, the Queen, Seven Rivers, Yates, and Tansill Formations of the Artesia Group (fig. 2). Ochoan units postdate demise of the Guadalupian reef system and include, from oldest to youngest, the Castile (restricted to the Delaware Basin), Salado, Rustler, and Pierce Canyon/Dewey Lake Formations (fig. 2).

The Guadalupian was a period when many of Earth's cratonic masses were in close proximity following continental collisions that commenced during the Pennsylvanian. The South American craton was adjacent to the southern region of the North American craton (figs. 5, 6). Early Pennsylvanian collision of these continental masses created numerous uplifts and basins and set the stage for the depositional patterns that characterized the later Pennsylvanian and Permian systems. During the Guadalupian, the Permian Basin region became increasingly tectonically quiescent, and the climate was dominantly arid. In contrast to earlier Permian depositional patterns, carbonate sedimentation was limited, whereas evaporite and redbed deposition was widespread. Desert eolian and associated aqueous sedimentary environments prevailed on land, whereas restricted-marine conditions that included low biotic diversity and abundance and widespread precipitation of evaporites characterized shallow subtidal, peritidal, and nearshore areas. The Midland Basin subsided slowly and remained relatively shallow (evaporitic), even during sea-level highstands. The Delaware Basin, however, continued to subside at considerably greater rates, and water depths ranged from 1,000 ft (305 m) to 1,800 ft (549 m) (Garber and others, 1989, citing King, 1948; Newell and others, 1953; and Silver and Todd, 1969). By late Guadalupian time the Midland Basin was filled and hosted mainly evaporite and terrestrial siliciclastic deposition. A persistent gap in the Guadalupian reef trends was maintained in Brewster/Pecos County, to the west of the Glass Mountains. Here the intracratonic basin was open to the extracratonic ocean system through the Hovey Channel (fig. 1).

Shallow basinal areas were in the process of infilling with mainly siliciclastics and evaporites while shelves were dominated by carbonate and evaporite deposition during sea-level highstands and by siliciclastic deposition during lowstands. Carbonate buildups were subjected to subaerial weathering during lowstands, and shelf-interior siliciclastics and shelf-margin carbonate debris were shed onto submarine slopes and deep-basin floors in the Delaware Basin (Delaware Mountain Group).

During the Ochoan both the Midland and Delaware Basins became filled, initially with evaporites and, finally, by siliciclastics (fig. 7). Appearance of widespread intracratonic fluvial and lacustrine deposition during the Late Triassic signaled onset of net deposition during overall wetter conditions after a protracted period of net nondeposition that accompanied the continental emergence that prevailed earlier in the Triassic (McGowen and others, 1979).

DEPOSITIONAL FACIES, DIAGENESIS, AND CONTROLS ON POROSITY DEVELOPMENT

Although formations of the Artesia Group are discussed as geologically distinctive units in the literature, they comprise generally similar facies, with similar lateral and vertical associations. All the Artesia Group units on the Northwest Shelf and western Central Basin Platform were deposited shelfward of the Guadalupian (Goat Seep/Capitan) reef complex in depositional settings dominated by carbonates in outer shelf positions, by evaporites and siliciclastics in middle shelf positions, and by siliciclastics in the most shelfward positions. More basinward positions on the evaporitic shelf are dominated by anhydrite, and more shelfward positions by halite. The characteristics of depositional cycles and diagenetic facies are also similar. The paleogeography was somewhat different on the east margin of the Central Basin Platform and the Northern Shelf of the Midland Basin, where carbonate strata thinned and equivalent units became evaporitic and siliciclastic. Nonetheless, primary facies and facies tracts associated with the Guadalupian hydrocarbon province on the shelves are similar. The differences between formations at any given location reflect differences in overall relative sea-level setting, within which depositional facies developed and the distance to siliciclastic source areas varied. Location-specific differences in vertical facies associations have compelled geologists to group intervals into formations. It is important to recognize, however, that a given set of facies associations that distinguishes the Queen Formation in one area may be similar to that of a section located farther shelfward in the Seven Rivers Formation. For these reasons it is most instructive to discuss Artesia Group facies rather than formation-specific facies.

Artesia Group facies are highly cyclic; facies components vary systematically vertically and geographically. In the most basinward areas of the platform, carbonate and sandstone typically compose a depositional cycle. In most of the cycles observed in cores during this study, sandstones are interpreted to represent transgressive-leg depositional cycles, and carbonates represent highstand, or the upper part of cycles. In progressively updip positions, carbonates diminish in abundance and anhydrite increases. In the still more updip areas, halite becomes common. In the most proximal areas, siliciclastics are dominant. Artesia Group carbonate and evaporite facies examined in core during this study commonly contained varying abundances of admixed siliciclastics and were compositionally transitional to overlying siliciclastic strata.

Siliciclastics are the primary reservoir facies in the Artesia Group, whereas relatively impermeable carbonates and evaporites provide updip occlusion of interparticle porosity and form top seals. Porous, grain-rich carbonates locally may provide minor secondary production in downdip positions.

Artesia Group Stratigraphy

The Artesia Group includes, from oldest to youngest, the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations. This report focuses on the middle and upper formations of the Artesia Group, which all contain similar facies and facies tracts. All were deposited shelfward of the Guadalupian Goat Seep and Capitan "reef" trends. The Goat Seep developed on an unconformity located on the Grayburg shelf margin (Fekete and others, 1986; Franseen and others, 1989). Previous workers considered the Goat Seep to be equivalent to the Grayburg (for example, Silver and Todd, 1969).The Goat Seep and Capitan are vertically separated by the Shattuck sandstone member of the Queen Formation (Newell and others, 1953). Designation of the Goat Seep and Capitan Formations as reefs is historical. Early geologic researchers envisioned these facies as shelf-margin barriers that resided near and slightly above sea level (for example, Newell and others, 1953), that is, at the shelf crest. More recently it has been advanced that the Goat Seep and Capitan are composed largely of algally bound shelf detritus and, considering their correlation to exposure surfaces in more updip positions, are more properly interpreted as shelf-margin-aligned submarine mounds (for example, Garber and others, 1989; Kerans and Harris, 1993). The facies located at the shelf crest are now recognized as pisolite-bearing shoals and closely associated peritidal facies (for example, tepee structures) that occur shelfward of the Capitan and Goat Seep (Newell and others, 1953; Thomas, 1968; Dunham;

Smith, 1974; Esteban and Pray, 1977, 1983; Borer and Harris, 1989, 1991; Garber and others, 1989; Neese, 1989; Parsley and Warren, 1989; Kerans and Harris, 1993).

Division of Artesia Group intervals into formations is originally based on lithostratigraphic distinctions at type sections. On the basis of lithology defined in type sections, Artesia Group formations are readily correlated for great distances (even hundreds of miles) across the Permian Basin region. This correlation is facilitated by the stratigraphic alternation between siliciclastic-dominated sections (Queen and Yates Formations) and carbonate- or evaporite-dominated sections (Grayburg, Seven Rivers, and Tansill Formations). From a regional point of view, the Artesia Group records migrations of similar carbonate-siliciclastic-evaporite facies tracts in response to 3rd-order (approximately formation scale) relative sea-level variations (Meissner, 1972; Borer and Harris, 1991). The Queen and Yates Formations are characterized by thick accumulations of siliciclastics in areas that are relatively close to the Northwest Shelf and Central Basin Platform shelf margins. In contrast, Seven Rivers and Tansill Formation siliciclastic-rich facies depocenters are displaced to more shelfward positions.

Each formation is characterized by cyclic vertical facies successions that reflect higher-order relative sea-level variations. Ideal vertical successions of facies vary along the shelf profile. In more seaward positions, cycle bases include transgressively reworked terrigenous siliciclastic facies overlain by upward-shoaling carbonates (figs. 8, 9) In more shelfward positions, carbonates are less abundant, include displacive and replacive anhydrite, and are overlain by bedded anhydrite, siliciclastic-bearing anhydrite, and anhydrite-bearing siliciclastics (sabkha or evaporative lagoon environments) (fig. 9). Still farther shelfward, carbonates are absent, and massive halite and halite-bearing siliciclastics overlie anhydrite facies (figs. 9, 10). In positions even farther upslope, eolian siliciclastics may locally overlie evaporite facies. During 3rd-order relative sea-level fall, higher-order cyclic vertical facies successions in basinward positions are replaced by those typical of more shelfward positions.

Permian shelf strata crop out mainly in the Guadalupe Mountains of Texas and New Mexico and nearby areas. These areas include part of the Northwest Shelf and northwestern Delaware Basin. Exposures of the Queen and Yates Formations are dominantly near-reef, carbonate equivalents of intervals elsewhere dominated by siliciclastics and evaporites. Other exposures occur in the Glass and Apache Mountains of West Texas, which include along-strike equivalents of Guadalupe Mountain exposures. Other limited exposures occur in small areas in the drainages of the Pecos, Upper Colorado, and Brazos Rivers. These latter two areas are part of the Eastern Shelf of the Midland Basin, where siliciclastics and evaporites dominate the Upper Permian section. Most of the Permian Basin region is covered by younger deposits that include the Upper Triassic Dockum Group, Lower Cretaceous Fredericksburg Division, Neogene Ogallala Formation, and Quaternary cover sand.

Yates Formation

Yates facies have been described in more detail than the other middle and upper Artesia Group intervals, probably reflecting their significance as a hydrocarbon play. The similarity of facies among the formations of the Artesia Group makes the very detailed descriptions of the Yates invaluable for providing insights into the Queen, Seven Rivers, and Tansill Formations. Cores from the Queen, Seven Rivers, and Yates Formations examined for this chapter show strong similarities to those of published studies. The Yates Formation will therefore be discussed before the other formations of the Artesia Group.

Stratigraphy, Type Section, and Regional Correlation

The siliciclastic-rich Yates Formation is in the Artesia Group (Tait and others, 1962) and is bounded bottom and top by the Seven Rivers and Tansill Formations, respectively. Except for the Delaware Basin, the Yates has been correlated everywhere in the rest of the greater Permian Basin, including the Palo Duro Basin. Thickness of the unit is more than 300 ft (91.4 m) in the back-reef area (Andreason, 1992). In the east (Scurry County) the Yates Formation thins to about 150 ft (45.7 m) (Dickey, 1940). Mear and Yarbrough (1961) suggested that the Sumrall Douglas Well No. 5 in Yates field, Pecos County, be designated as the type section and redefined the Yates Formation as including all strata between the Seven Rivers and Tansill Formations. Previously the Yates Sand was described from Yates field (Gester and Hawley, 1929), but the description included only 50 ft (15.2 m) of anhydritic sandstone and did not include any of the carbonates or evaporites that underlie or overlie the sandstone-dominated interval. Abundant large, frosted sand grains were a diagnostic indicator of Yates facies, although they also occur in some Queen and Seven Rivers sandstone intervals.

Stratigraphic equivalents elsewhere in the Permian Basin include the middle part of the Altuda Formation in the Glass Mountains and the uppermost part of the Whitehorse Group in west-central Texas. In sequence stratigraphic terms, the lower Yates composes the shelf component of a composite sequence (CS-13 of Kerans and Kempter, 2002) (figs. 2, 4). According to field correlations that led to these sequence divisions, the approximate Delaware Basin equivalent (Delaware Mountain Group) of the Yates is the Rader member of the Bell Canyon Formation. The upper part of the Yates, along with the overlying Tansill Formation, composes the shelf component of another composite sequence (CS-14). Delaware Basin equivalents of CS-14 include, from older to younger, the McCombs and Lamar carbonate members, as well as several siliciclastic members that interfinger with the carbonates (figs. 2, 4). Yates-equivalent Delaware Basin strata are discussed elsewhere in this volume.

The Yates is one of the two overall siliciclastic-dominated, Guadalupian-age formations of the Permian Basin shelf. It is similar to the Queen Formation in many ways. Both are located landward of the Permian reef complexes that rim the Delaware Basin, and both comprise similar facies types, cyclic relationships between facies, and geographic distribution of facies. In both formations, sandstone is arkosic (fig. 11).

Subsurface Recognition and Correlation

The Yates Formation is recognized as an interval composed of thick sandstone beds and subordinate carbonate and evaporite that are overlain by thick carbonate or evaporite of the Tansill Formation and underlain by thick carbonate or evaporite of the Seven Rivers Formation. Occurrence of carbonate or evaporite in stratigraphically bounding units depends on position along the basin-to-shelf profile. Historically the top of Yates has been recognized by presence of well-rounded, frosted, medium-grained sand (for example, Gester and Hawley, 1929). Such material is not everywhere present in the Yates, however, and also occurs locally in the Queen and Seven Rivers. Their occurrence probably depends on the presence or former presence (in the case of marine reworking) of eolian facies, coarser grains of which may represent interdune lag deposits (Nance, 1988a, b).

In the absence of core, readily available gamma-ray logs are generally adequate for recognition and correlation of the Artesia Group. Yates carbonates and evaporites (anhydrite and halite) have significantly lower gamma-ray values than do siliciclastics (figs. 8, 10). The higher values for siliciclastics are controlled by the high content of K-feldspar in the subarkosic to arkosic sandstone that is typical in the Permian Basin. A problem arises locally when only a gamma-ray log is used to pick the top of the Yates. In some areas the Tansill contains uranium-bearing dolomite and magnesite intervals that can be misinterpreted as siltstone beds (Garber and others, 1989. Elevated gamma-ray responses in the Tansill may compel the log analyst to pick the top of Yates within, or even at the top of, the Tansill. Availability of acoustic or density logs provides an independent basis from which to make a more appropriate interpretation, however, because siltstone density is generally much lower than that of carbonate.

Correlations are further facilitated by the laterally extensive tabular geometry of facies and by the basin-to-shelf facies tract structure whereby carbonate transitionally merges with stratigraphically equivalent evaporite. Yates rock-type recognition is facilitated in wells for which density, acoustic, or caliper logs are available. Carbonate- and anhydrite-dominated facies have higher bulk densities, lower density porosities (fig. 12), and lower acoustic-interval transit times than do siliciclastic-dominated facies. Halite-dominated strata have low gamma-ray values coupled with very low densities and interval transit times. Caliper logs show borehole enlargement in intervals of poorly cemented siliciclastics (fig. 12), as well as in intervals of halite-bearing strata if halite-undersaturated, water-based fluid was used to drill the well. Values of various geophysical well log responses from representative Upper Permian rock types are presented in the facies section of this chapter.

Regionally the Yates Formation is distinguished by a greater abundance of siliciclastics relative to other facies compared with most of the remaining Upper Permian section. However, textural, compositional, and diagenetic characteristics observed in Yates siliciclastics are present in the siliciclastic facies of the other Artesia formations. Sandstones are typically well- to very well sorted, and grains finer than coarse silt sized are not abundant. Feldspar is a common accessory mineral in Artesia sand and siltstone facies (fig. 11), and secondary porosity developed from its dissolution is common. One of the most notable features of some Yates sandstones is the presence of well-rounded pitted or frosted quartz grains within the coarser sand fraction (Page and Adams, 1940; Mear and Yarbrough, 1961). Frosted grains have also been described in the Queen (Nance, 1988a, b).

Yates siliciclastics and associated carbonate and evaporite were deposited landward of the Capitan reef system. Consequently, carbonate (mainly dolomitic mudstone and pisolitic dolopackstone and dolograinstone) is more relatively abundant in seaward positions on the Yates shelf. Evaporites (halite and anhydrite) are increasingly important in inner-shelf positions, whereas major sandstone reservoir facies occur in middle-shelf positions.

The most comprehensive published summaries of Yates siliciclastic facies are those of Borer and Harris (1991) and Andreason (1992). Borer and Harris (1991) recognized six paleogeographically related, siliciclastic-dominated subfacies on the basis of cores from the Northwest Shelf and the western Central Basin Platform. They also discussed associated dolostone and evaporitic facies, although in less detail. Borer and Harris (1991) also provided useful graphic depictions of well log responses to various facies.

Andreason (1992) studied Yates cores and well logs from North Ward-Estes field, located on the west margin of the Central Basin Platform in Ward County, the largest and most productive Yates field. Andreason (1992) classified siliciclastic facies according to their general sedimentary structure and interpretations of depositional environments that were bolstered by mapping of well log facies. Andreason (1992) discussed Yates carbonate and evaporite facies in more detail than Borer and Harris (1991), although sandstone is the primary Yates reservoir facies. Andreason (1992) also provided core-plug porosity and permeability data. Both studies focused on facies from the outer shelf and outer-inner evaporitic shelf. None of the investigators discussed halite facies or evidence of their former presence.

Borer and Harris (1991) suggested that three main shelf settings could be distinguished on the basis of resident facies and facies associations (fig. 9). The outer shelf began where formation thickening accelerated abruptly to the Capitan reef shelf break, a distance of 3 to 4 mi (5 to 6 km). Lowstand deposits are composed mainly of siliciclastic facies. Highstand deposits are composed mainly of carbonate in downslope areas and evaporite-bearing carbonate or evaporite (anhydrite and halite) in upslope areas. Pisolite shoal carbonate facies are abundant and mark the topographically most elevated position on the outer shelf.

Artesia Group Core

Yates siliciclastics, as well as siliciclastics in other Artesia intervals, are represented by siltstone and very fine to fine-grained sandstone. A very minor fraction of prominent spherical medium-grained sand occurs locally in all Artesia Group formations. Coarser grained sand and gravel-sized particles are limited mainly to intraclastic facies or collapse breccias. Rock colors are generally red, gray, or brown. Feldspar, often partly dissolved, composes a prominent fraction, and most of the siliciclastics can be classified as subarkose to arkose. Kaolinite, a product of feldspar weathering, is commonly present (Borer and Harris, 1991). Porosity and reservoir potential are best developed in fine-grained sandstone where feldspar has been significantly dissolved. In more basinward positions, dolomite matrix is a significant component, and siliciclastics grade laterally into siliciclastic-bearing dolostone. Where siltstone or sandstone overlies or underlies dolomite, a compositionally transitional interval between the two end members is commonly present. In more shelfward positions, interstitial anhydrite is a prominent component, and anhydrite nodules are commonly present. The plugging of sandstone porosity by dolomite and evaporites in upslope positions and in units vertically adjacent to porous fine sandstone forms the primary reservoir architecture (stratigraphic traps) in the Artesia Group.

Borer and Harris (1991) performed extensive petrographic analyses on cores from the Yates Formation on the Central Basin Platform and the Northwest Shelf and provided a petrographically based classification scheme of facies types. Andreason (1992) described cores from North Ward Estes field on the west edge of the Central Basin Platform and provided a classification scheme based on texture and sedimentary structures. There is considerable overlap of the two classification systems. However, there generally is not a one-to-one correspondence between the descriptive categories from each. The classification system of Borer and Harris may be more helpful when comprehensive petrographic analyses are, whereas the macro-scale descriptions provided by Andreason (1992) (based largely on texture, readily observed compositional features, and sedimentary structures) may be more helpful to one who is describing core without the advantage of thin sections.

Facies Classification Based on Petrographic Criteria

Outer-shelf facies

The idealized outer-shelf siliciclastic facies tract include, in downslope order, (1) dolomitic subarkosic siltstone and sandstone, (2) anhydritic siltstone and sandstone, and (3) bioturbated kaolinitic dolomitic quartz sandstone (fig. 9).

The dolomitic subarkosic siltstone and sandstone facies ranges from mudstone to sandstone. Compositionally this facies can be classified as a micaceous lithic subarkose. Potassium feldspar and plagioclase are subequally represented and compose 5 to 15 percent of typical samples. Dissolution of some feldspar grains is apparent. Volcanic, metamorphic, and chert constituents compose most of the lithic fragments. The facies is typically green-gray and generously interbedded with algal dolomudstones and minor pisolite packstones. Thin interlaminae of dolomudstone occur and may record short-term rises in relative sea level or shifts of siliciclastic depositional axes. Vertical transitions of this facies from and to dolomudstone strata are typically mud rich, with lower contacts tending to be sharp and upper contacts typically transitional. The character of the dolostone-siliciclastic contacts may signify rapid fall and slow rises of sea level, respectively. Intercalation with carbonates suggests a distal tidal-flat to shallow subtidal depositional setting for dolomitic siliciclastic facies.

The anhydritic siltstone and sandstone facies ranges from very fine grained, sandy, argillaceous siltstone to silty, very fine grained sandstone. Compositionally this facies can be classified as anhydrite- and dolomite/magnesite-bearing subarkose to arkose. Detrital grains compose 50 to 60 percent of the facies. Anhydrite, dolomite, and magnesite interstitial cements compose the remaining 40 to 50 percent of the rock, although some matrix dolomite appears to be diagenetic. Monocrystalline quartz dominates the framework, with feldspars composing 20 to 30 percent. Largely Na-rich plagioclase is altered or dissolved to varying degrees. Rock fragments, heavy minerals (primarily ilmenite), and mica each compose approximately 1 to 5 percent of the remaining framework. Volcanic, metamorphic, and chert constituents compose most of the lithic fragments. Larger, well-rounded, and pitted or frosted quartz grains also occur in minor proportion. Sorting varies from moderately good to poor and is generally better in coarser grained examples. Siliciclastic laminae may be graded, and very fine grained sand lenses are common. Red, detrital, illitic clay composes up to 20 percent of the matrix in the siltstone and occurs as laminae or grain coats. The facies typically is red and alternates with thicker bedded pisolite-shoal-complex dolomite. Dolomites record shoaling cycles characterized by basal dolomudstone that grades up through fenestral dolowackestone to packstone and, ultimately, to intraclastic and pisolitic dolopackstones and grainstones. Tepee and fenestral voids are typically filled with anhydrite, and desiccation features are evident. Intercalation with shelf-crest peritidal carbonates, presence of evaporite cements, red color, and presence of frosted grains suggest an evaporitic tidal-flat depositional setting in which precursor siliciclastics were transported to the area by eolian processes.

Bioturbated kaolinitic dolomitic quartz sandstone ranges in size from clay to medium-grained sand. Detrital clay composes less than 5 percent and is not red. Quartz composes up to

70 percent of the facies, with dolomite cement or recrystallized matrix and authigenic kaolinite composing most of the remainder. Borer and Harris (1991) indicated that kaolinite fills secondary porosity following feldspar solution. Well-rounded pitted or frosted quartz grains occur within the coarser fraction as thin laminae or are dispersed. The facies is typically gray and associated with carbonates similar to those interbedded with the red anhydritic siltstones and sandstones, except that carbonate mudstone is more prominent and allochems are finer grained. Desiccation features are absent, and pore-filling anhydrite is absent. Pores are filled with fine-siliciclastic-bearing dolomicritic cement. Thinly bedded fusulinid packstone also occurs. Intercalation of this siliciclastic facies with subtidal carbonates, bioturbated fabric, and presence of frosted grains suggests deposition in a shallow subtidal setting where the clastics were transported to the nearshore terrestrial area by eolian processes and were ultimately transported into the subtidal zone by storm surge or fluvial-deltaic processes.

Middle-shelf facies

Middle shelf siliciclastic facies tract include, updip to downdip, (1) arkosic sandstone and (2) argillaceous siltstone (fig. 9).

Arkosic sandstone (fig. 13A) is the dominant reservoir facies in the Yates and ranges in grain size from silty, very fine grained to fine-grained sandstone and is typically well to very well sorted. Similar reservoir facies occur in the Queen in North Ward-Estes field (fig. 13B). It is generally poorly consolidated. Detrital clay occurs in association with wispy, plane, or ripple laminae. Feldspar solution has produced secondary porosity locally. Authigenic feldspar, dolomite, anhydrite, and corrensite (Mg-Fe smectite) cements partly fill pores. The facies, generally light-brown in color, is associated with relatively thinner intervals of dolomudstones; however, a transitional interval of argillaceous siltstone usually occurs between the sandstone and dolomite. Intercalation of these sandstones with thinly bedded dolomudstone and argillaceous siltstone, very good sorting, and vague, disrupted, ripple lamination with fine-grained drapes suggests deposition along the shelfward margins of shallow lagoons located shelfward of the pisolitic shelf crest. Finer grained clastics were probably winnowed by wind action. The brown color may be oil staining, judging from core examinations for this chapter.

Argillaceous siltstone ranges from mudstone to argillaceous silty sandstone. Clay occurring in abundances of 5 to 25 percent is present as wispy laminae, intraclasts, and disseminated matrix. Argillaceous siltstone is typically dark-gray and occurs at the base and top of arkosic sandstone intervals. Intercalation of this facies with arkosic sandstone that is interpreted to be deposited on the shelfward margins of lagoons suggests a nearby environment for argillaceous siltstone, probably the lagoons. Deposition of the finer grained siliciclastics over sandstones probably occurred during a time of lagoonal expansion onto the margins where sandstone was previously deposited. Silt-sized particles would have been winnowed from updip deposits and trapped in lagoons.

Inner-shelf facies

The inner shelf is characterized by (1) evaporites and (2) red siliciclastics (fig. 9). According to descriptions provided by Borer and Harris (1991) and core described for this report, evaporite intervals may be dominated by anhydrite (fig. 14A,B) or halite (figs. 14C), with halite occupying more shelfward areas. In intervals with no halite, the former presence of halite is suggested by compacted anhydritic or siliciclastic components that are interpreted as representing the insoluble fractions of halite-bearing strata (fig. 14C). Abundance or absence of primary dolomite strata probably reflects paleogeographic proximity to or removal from normal marine conditions, with more abundant carbonate anticipated to have been deposited in more basinward areas at any given time. However, some of the dolomite fabrics (ghosts of gypsumlike swallowtails) probably record carbonate replacement of formerly occurring sulfate. And darker red colors (iron sulfide) in some of the siliciclastic siltstone and mudstone that, in places, underlie dolostone may record percolation of sulfide-rich solutions generated during the replacement process. Halite-solution features are more abundant in core, with greater relative amounts of dolomite in close stratigraphic proximity. It is reasonable to expect that halite dissolution in any depositional cycle occurred preferentially in paleo-basinward areas during the next marine transgression.

The primary siliciclastic facies in the inner shelf setting are argillaceous siltstone and sandstone, which are compositionally micaceous subarkose to arkose. Detrital illitic clay is abundant, and authigenic anhydrite and dolomite occur. However, dolomite abundance decreases toward eventual absence in more updip paleogeographic areas. Argillaceous siltstone from the inner shelf is typically red from hematite stain.

Facies Classification Based on Texture and Sedimentary Structure Criteria

Andreason (1992) used a depositional-fabric approach to classification of siliciclastic facies that he interpreted from core in North Ward-Estes field. Facies-specific porosity and permeability data reported from North Ward-Estes field are presented in table 1.

Table 1. Log responses and core test results for Yates facies, North Ward-Estes field, Ward County (Andreason, 1992). Halite values are from the author, and they are based on responses from University 3210-2 well, Andrews County.

	Log response		**Core test**			
Facies	Gamma ray (API)	Bulk den. (g/cm^3)	Por. range (%)	Avg. por. (%)	Perm. range (md)	Avg. perm. (md)
Disturbed silic.	70-100	2.38-2.56	5-29	14	0.1-68	7
Homog. silic.	50-70	2.25-2.45	7-26	16	0.5-4.90	42
Bioturb. silic.			9-14	11	0.4-10	2
Lamin. silic.			8-19	12	0.2-15	
Carbonate	12-63*	2.69-2.88	Negligible	Negligible	Negligible	Negligible
Anhydrite	5-36*	2.85-2.99	Negligible	Negligible	Negligible	Negligible
Halite	5-36*	2.17-2.36**	Negligible	Negligible	Negligible	Negligible

*Estimated higher value is admixture with siliciclastics
**Estimated higher value is 50% admixture with sandstone

Andreason (1992) recognized four basic siliciclastic facies on the basis of their general depositional fabric: (1) disturbed (with bedded and intraclastic subfacies), (2) homogenized, (3) laminated, and (4) bioturbated.

Disturbed facies

Disturbed facies range in degree of disturbance of original even lamination (fig. 13D). Presence of cubic ghosts after formerly present halite in some examples suggests that haloturbation was the primary cause of sediment disturbance. Some examples still include halite crystals (fig. 14D) and may have been produced in a sabkha setting that was sufficiently updip to be unaffected by subsequent inundation by marine-derived, halite-undersaturated water. The facies is argillaceous in places. Andreason (1992) interpreted cubic ghosts and salt-ridge structures to indicate development in coastal and continental sabkha settings on the basis of comparisons with examples from Saudi Arabia (Fryberger and others, 1983), Mexico (Fryberger and others, 1988; Thompson, 1968), Abu Dhabi (Kendall and Shipwith, 1968), India (Glennie and Evans, 1976), and New Mexico (Fryberger and others, 1988).

Homogenized facies

Homogenized facies include sandstone and silty sandstone that generally lack well-developed sedimentary structures, although some vague lamination may be evident (fig. 13A, B). They are the primary reservoir facies in the Yates and Queen middle-shelf trend and correspond to the light-brown arkosic sandstone of Borer and Harris (1991). This facies contains as much as 4 percent of the frosted or pitted medium sand grains for which the Yates is noted (Page and Adams, 1940; Mear and Yarbrough, 1961). Beds range from 6 inches (15.2 cm) to 12 ft (3.7 m) in thickness, which Andreason (1992) interpreted as representing beach-ridge deposition as eolian dunes and sand sheets, sand-rich sabkhas, and shorefaces. Homogenization of original dune crossbedding presumably reflects coastal marine reworking and tidally driven liquefaction. Proximity to evaporite-undersaturated marine water is interpreted as promoting preservation of interparticle porosity by maintaining conditions unfavorable to evaporite precipitation or preservation. Homogenized facies geometries are lenticular and are not everywhere the dominant facies of specific sand intervals on the middle shelf.

Laminated facies

Laminated facies have preserved original sedimentary structures. Subfacies include ripple- and plane-bedded varieties. Ripple-laminated facies (lower and middle areas in figs. 13C, 15A) typically occur as beds less than 1 ft (0.3 m) thick, sometimes within otherwise disturbed facies, and are interpreted as recording seasonal flooding of sabkha flats. Planar-laminated facies (most of fig. 13C), typically occurring as intervals less than 1 cm thick, are characterized by graded bedding that is interpreted as recording sedimentation from suspension in ponds following storms or subtidally during eustatic sea-level rises. The latter explains the facies occurrence at the base of many shoaling cycles.

An example of ripple cross-laminated, very well sorted, fine sandstone is shown in figure 15A. The fine laminae are similar to those interpreted to be eolian by Nance (1988a, b) from the Queen in Palo Duro Basin. These features are not common in cores described from the west margin of the Central Basin Platform, where plane-laminated and disturbed-ripple-laminated fabrics in siliciclastics are more common. Rarity of eolian-produced sedimentary structures may reflect marine reworking of lowstand terrestrial siliciclastics that is expected on shelf areas proximal to the shelf margin. Inclined cross-laminated sandstone facies are more commonly reported from Artesia Group rocks on the east margin of the platform (for example, Mazzullo and others, 1992).

Bioturbated facies

Bioturbated facies include a range of biologically modified sediments, including burrows, mottling not related to evaporites, and anhydritic root-cast nodules. Burrowed and mottled varieties are reported to be located preferentially on the paleo-seaward side of the middle shelf, where they occur in cycle bases beneath carbonates. Bioturbated facies are the most uncommon of the facies in Andreason's (1992) classification, which testifies to the rarity of infauna and vegetation in Artesia Group terrestrial depositional environments.

Redbeds

Andreason (1992) noted that all four main facies locally could be red in color (for example, figs. 13C, 14C, D, 15, 16) but observed that most redbeds comprised disturbed facies. Redbeds signify pervasively oxidizing environments of the inner shelf and generally incorporated more interstitial anhydrite than reduced equivalents of similar coeval facies that occur downdip. Redbeds are less common in paleo-seaward positions presumably because sedimentation rates were higher and reducing conditions could thus be maintained more easily. Anhydrite is more common on the inner shelf than in more paleo-seaward positions. Andreason (1992) proposed that the scarcity of downslope anhydrite reflects the presence of porous and permeable beach-ridge complexes, which provided avenues for circulating evaporite-undersaturated water to adjacent sabkha settings. This development provides the porous middle-shelf reservoirs and updip evaporite plugging of porosity that characterizes stratigraphic traps in the Yates play, as well as in other Permian shelf plays.

Carbonates

Largely because the world-class exposures of Upper Guadalupian strata in the Guadalupe Mountains compose reef and proximal back-reef facies, many of the descriptions of carbonate facies originate from investigations in that region. An excellent succession of those facies was cored on the north margin of the Delaware Basin (Gulf PDB-04: Garber and others, 1989). Other cores include those of Andreason (1992) from North Ward-Estes, where dolomud/wackestone dominates Yates carbonate facies, and those of Spencer (1987) from Yates field, where algal-laminated pellets and calcisphere-rich dolopackstone dominate Queen carbonate facies.

Carbonates are the most prominent shelf facies in proximal back-reef positions and grade shelfward from cross-laminated (fig. 17A) to vaguely laminated grainstone and packstone (fig. 17B) deposited on or around shoals to pisolitic shoals that formed the topographically highest area on the outer shelf (fig. 17C) to massive, bioturbated dolomudstone deposited in quiet lagoons (fig. 17D) to finely laminated dolowacke/mudstone deposited on tidal flats (fig. 18A, and lower half of fig. 18B). Carbonates also occur in fine interlaminations, with anhydrite (originally gypsum; fig. 16 and upper half of fig. 18) deposited in brine pools that developed in depressions shelfward of lagoons.

Yates carbonate strata in North Ward-Estes field are dominantly dolostone. Although dolomicrite is dominant, organic and inorganic allochems are present in some intervals, and admixed siliciclastics are ubiquitous. Moldic and vuggy porosity is most common, is usually anhydrite- or dolomite-cement filled, and usually not in significant reservoirs. Andreason (1992) suggested an ideal shoaling sequence in carbonate intervals that included, from base to top, (1) fossiliferous peloidal dolowackestones to grainstones, (2) peloid/oncoid dolowackestones to grainstones, (3) fenestral-cryptalgalaminite dolomicrite, and (4) intraclastic breccias with admixed siliciclastics. Siliciclastic facies located immediately beneath carbonate strata probably record transgressive reworking of lowstand siliciclastic accumulations. If so, then these rocks represent the transgressive record at the base of a shoaling cycle rather than at the top.

From the lower Tansill Formation in the Guadalupe Mountains Neese (1979) described back-reef fossiliferous dolowackestone and packstone (including ostracodes, gastropods, forams), shelf-crest (pisolite and tepee structures with erosion surfaces), and intertidal peloid grainstone with admixed siliciclastics facies. Parsley and Warren (1989) described Tansill back-reef facies from Dark Canyon that included, from oldest to youngest, (1) subtidally deposited wackestone and poorly sorted packstone; (2) subtidally and intertidally deposited laminated and crossbedded, well-sorted, skeletal-peloid grainstone; and (3) peritidally deposited laminated mudstone and fenestral peloid packstone/wackestone. A barrier-island facies assemblage included tepees and coarse-grained pisolite that were interbedded with fenestral mudstone, fenestral wackestone/packstone, and local calcisphere-bearing mudstone/wackestone. A lagoonal assemblage included dolomitized, extensive, calcisphere-rich mudstone and wackestone, algal-laminated packstone, and peloid-intraclast packstone.

Mazzullo (1999) recognized shoaling facies in the Tansill (also from Dark Canyon) on the basis of observation of (1) subtidally developed bioclastic wackestones, packstones, and graded and locally cross-stratified grainstones, as well as biostromes; (2) fenestral and locally desiccated mudstone interpreted to have developed on peritidal flats; and (3) admixed subtidal and peritidal deposits interpreted to have been developed on shorefaces.

Evaporite facies

The prominence of bedded evaporite over carbonate marks the transition from middle- to inner-shelf environments. Similar to Permian carbonate-evaporite facies tracts from the evaporite-rich Palo Duro Basin in the Texas Panhandle, the updip increase in abundance of Yates evaporites signifies progressive evaporative evolution of marine-derived water, with updip distance from normal marine environments that existed seaward of the pisolite shoal zone.

Andreason (1992) recognized two main evaporite facies in Ward-Estes field, both of which are dominated by sulfate: (1) nodular anhydrite (figs. 14A, 18D) and (2) massive (essentially homogeneous) anhydrite (no photo). Nodular facies overlies massive facies in the east part of the field and probably records infilling of playas or evaporitic lagoons. Apart from cubic ghosts after halite and deformation in disturbed siliciclastic facies, halite-bearing rocks were not indicated.

Nodular anhydrite facies were constructed of nodules with no less than 40 percent supporting dolomite or siliciclastic matrix. Andreason (1992) noted the similarities between Yates nodular anhydrite and that from Trucial Coast sabkhas, where anhydrite is precipitated in the capillary zone. The thickness of nodular anhydrite accumulations is controlled by limits on capillary-zone thickness, which is as much as 6.6 ft (2 m) in siliciclastics and less than 3.3 ft (1 m) in carbonate-dominated terrain. However, slowly rising sea level is thought to produce thicker nodular intervals by raising the capillary zone into accumulating host sediments (Warren and Kendall, 1985).

Massive anhydrite from North Ward-Estes contains less than 20 percent dolomite or siliciclastic matrix that is typically vertically oriented as stringers between nodules. The facies, sharply bounded at its base and top, is most prominent in the east part of Ward-Estes field.

Where overlain by dolostone, the boundary is corrosive and indicates the presence of gypsum-undersaturated water in the depositional environment. Where overlain by nodular facies, the section probably records infilling of brine pools.

A laminated variety of anhydrite is observed in some cores (fig. 14B). These probably record gypsum precipitation shallow pools, where tall crystals cannot develop or where agitation of the pool surface abrades crystals and distributes the debris in even layers.

Finely interlaminated anhydrite and dolomite (fig. 18C) occur in the evaporative inner shelf and were probably precipitated in brine pools free of siliciclastic influx. Anhydrite pseudomorphs after gypsum swallowtail twins are locally common and appear to be draped by fine laminae of dolomite. The alternations between anhydrite and dolomite reflect cyclic variations of salinity in the brine pool, whereby hydrochemical conditions oscillated between gypsum saturation and undersaturation. Fine laminations within the dolomite intervals may record algal growth (fig. 18A, B). In an ideal, complete depositional sequence, the vertical facies progression is anhydrite, halite, halite-mudstone (mud salt), and sandstone. Where sandstone overlies anhydrite, the original halite-bearing strata may have been disaggregated by dissolution of halite, and included siliciclastics reworked by erosive processes. These conditions develop in an evaporative lagoon or wind-deflated depression, where ponded water (groundwater source, perhaps) is already close to calcium sulfate supersaturation, and substrate moisture within the pond-margin sediment precludes eolian siliciclastic transport to the brine pool. Eventually the pool filled with gypsum, then halite. Siliciclastics along pool margins were occluded with evaporites, and eolian-transported siliciclastics covered the area. Cover sands were inundated with saline, near-surface groundwater through capillary action, and halite precipitated within the cover sands (fig. 14D). Eventual dissolution of the halite fraction produced the disturbed sedimentary fabrics described by Borer and Harris (1991) and Andreason (1992) (fig. 13D).

Solution-collapse breccia

Solution-collapse breccias comprise angular dolostone clasts either supported by a fine-grained siliciclastic (fig. 15B) matrix or supported as a clast-supported facies with dolomite-dominated matrix (fig. 18B). Clasts are typically cryptalgally laminated. Clasts are generally rotated chaotically and contrast with intraclastic breccias from more seaward positions that have more rounded clasts, which have imbricate orientations that suggest storm depositional processes. Judging from correlations of solution-collapse breccias with locations where massive anhydrite beds are preserved, it appears that dissolution of sulfide beds provided the loss of support for brecciated precursor strata (Andreason, 1992).

Andreason's (1992) data indicate that either normal sulfate-undersaturated marine or meteoric water could dissolve the evaporite facies. However, concentration of the zone of collapse on the seaward margin of massive anhydrite accumulations compelled Andreason (1992) to conclude that sulfate dissolution most probably occurred during marine transgression.

Halite facies

During the present study, several cores have been described that recorded evaporite precipitation and the former presence of evaporites. Evaporite facies include anhydrite, halite, and halite-mudstone that were deposited in and at the landward margins of broad, shallow brine pans (salinas and sabkhas). Extensive discussions of similar facies and conditions of deposition from the Queen/Grayburg interval in Palo Duro Basin (essentially the northern extension of the northern shelf of Midland Basin) can be found in Nance (1988a, b).

Halite facies and halite-dissolution facies include (1) massive, polycrystalline varieties; (2) admixtures with siliciclastics; and (3) compacted siliciclastic and sulfate residues after halite dissolution. Massive, polycrystalline halite (fig. 14C) occurs as mosaics of halite crystals. Intercrystalline stringers of anhydrite are often present and testify to the occasional reduction of salinity to below that of halite saturation. Occasionally it is possible to observe chevron-shaped ghosts in halite crystals that reflect incremental precipitation in the brine pool and entrapment of fluid inclusions (Fracasso and Hovorka, 1986; Nance, 1988a, b). In most instances, however, the halite deposits have been cyclically dissolved and reprecipitated so that relict zonation is lost. In cases where postdepositional halite dissolution has not occurred, siliciclastic admixtures with halite (uppermost part of fig. 19) often occur in intervals that directly overlie massive varieties. Siliciclastic fractions range from trace to dominant. Where halite has been completely dissolved, compacted mixtures of siliciclastics and anhydrite stringers are preserved (fig. 14C). Most, but not all, admixed siliciclastics are very fine grained (mud) and exhibit very little permeability so that they may provide a potential reservoir seal even in the absence of halite.

It has been hypothesized that dissolution of small halite crystals from laminated siliciclastics may have produced the disturbed aspect of laminations widely observed in Artesia siliciclastics (haloturbation), although bioturbation is also recognized as a potential influence. As relative-sea-level-controlled accommodation volumes were filled with sediment and rates of evaporation relative to influx of marine-derived water increased, developing higher-density, halite-supersaturated brines would be expected to percolate into tidal-flat sediment, displace less-dense marine water, and eventually precipitate interstitially varying amounts of halite in what might be considered a sabkha environment. Evaporite precipitation in tidal-flat sediments is anticipated to occur in positions basinward of the primary, halite-precipitating brine pools and, thus, be exposed to subsequent influxes of halite-undersaturated marine-derived water. What remains is an originally planar laminated fabric that has been displaced by crystal growth and eventual collapse during halite dissolution.

Queen Formation

Stratigraphy, Type Section, and Regional Correlation

Thickness of the Queen Formation, possibly exceeding 1,000 ft (304.8 m) in the Midland Basin, thins to about 130 ft (39.6 m) in Coke County on the Eastern Shelf (Mear, 1963). The Queen is the back-reef equivalent to the Goat Seep reef complex. The uppermost beds of the Shattuck sandstone member of the Queen overlap the Goat Seep and stratigraphically divide the Goat Seep from the Capitan complex (Silver and Todd, 1969; Ball and others, 1971).

The Queen is one of the two overall siliciclastic-dominated, Guadalupian-age formations of the Permian Basin shelf. It is similar to the Yates Formation in many ways. Both are located landward of the Permian reef complexes that rim the Delaware Basin. Both probably record periods of relative sea-level lowstand compared with those of the other Guadalupian formations (on the basis of relative siliciclastic abundance), and both comprise similar facies types with similar cyclic vertical facies progressions.

At the type section on the Northwest Shelf 2 miles south of the old Queen Post Office (40 mi (64.4 km) SW of Carlsbad, New Mexico) Moran (1962) characterized the Queen as 421 ft (128.3 m) of sandstone, sandy dolomite, and dolomite. The lower 41 ft (12.5 m) consists of crossbedded sandstone. At this location the Queen is overlain by Seven Rivers dolomite. A type well was defined by Tait and others (1962) in Artesia field (Eddy County, New Mexico), wherein the Queen was described as comprising 420 ft (128 m) of sandstone and anhydrite, with the uppermost 30 ft (9.1 m) composed of bimodal sandstone. The upper sandstone unit is part of the Shattuck Member (Newell and others, 1953), which is generally about 100 ft (30.5 m) thick over much of the shelf in the Guadalupe Mountains, except near the reef where it thins.

At Keystone field, a few miles shelfward of the Goat Seep reef, the 220-ft (67.1-m) Colby productive sandstone interval is equivalent to the lower half of the Queen Formation. Sandstone represents approximately 55 percent of the interval that also includes dolomite and anhydrite (Vanderhill, 1991).

At Yates field on the southeast tip of the Central Basin Platform, Queen facies include coarse-grained siltstone, very fine grained sandstone, and dolomite (Spencer and Warren, 1986). Within the siliciclastics are wispy clay streaks and dolomitic crusts. Intraclasts of dolomitic crusts are locally common. Dolomites include massive (bioturbated?) and laminated pellet packstone to wackestone.

Core representing the complete Queen interval from North Ward-Estes field in Ward County, Texas, was described for this chapter (fig. 20). Similar to Yates intervals described from other Guadalupian outer- to middle-shelf positions in the Permian Basin, the Queen in this area is composed of cycles of shallow water carbonates and siliciclastics. Carbonate is dominantly dolomudstone and wackestone, although thin packstone is locally common. These rocks contain pel-moldic porosity and oil staining. Megafossils are rare. Siliciclastics are mainly gray, well-sorted, very fine sandstone with varying portions of coarse silt. It has a red color in the lowermost 50 ft (15.2 m) of the interval. Very well sorted, fine-grained sandstone is subordinate but is very porous and permeable and comprises the primary hydrocarbon reservoir facies, as indicated by its brown color and petroleum odor (fig. 13A).

Subsurface Recognition and Correlation

The Queen Formation is recognized as an interval composed of thick sandstone beds and subordinate carbonate and evaporite that are overlain by thick carbonate or evaporite of the Seven Rivers Formation and underlain by thick carbonate or evaporite of the Grayburg Formation (fig. 20). The occurrence of carbonate or evaporite in stratigraphically bounding units depends on position along the basin-to-shelf profile.

In the absence of core, readily available gamma-ray logs are generally adequate for recognition and correlation of Queen end-member (pure anhydrite, carbonate, and siliciclastic) facies. Carbonates and evaporites (anhydrite and halite) have significantly lower gamma-ray values than do the siliciclastics (figs. 8, 10, 20). Higher values of siliciclastics are controlled by the high content of K-feldspar in the subarkosic to arkosic sandstone that is typical in the Permian Basin. Correlations are further facilitated by the laterally extensive tabular geometry of facies and by the basin-to-shelf facies tract structure, whereby carbonate transitionally merges with stratigraphically equivalent evaporite. Rock-type recognition is facilitated in wells for which density, acoustic, or caliper logs are available. Carbonate- and anhydrite-dominated facies have higher bulk densities, lower neutron porosities, and acoustic-interval transit times than do siliciclastic-dominated facies (figs. 12, 20). Halite-dominated strata have low gamma-ray values coupled with very low densities, interval transit times, and porosity (fig. 10). Caliper logs show borehole enlargement in intervals of poorly cemented siliciclastics, as well as in intervals of halite-bearing strata if halite-undersaturated, water-based fluid was used to drill the well. Values of various geophysical well log responses from representative Upper Permian rock types are presented in the facies section of this chapter.

Seven Rivers Formation

Stratigraphy, Type Section, and Regional Correlation

The Seven Rivers Formation in the Artesia Group (Tait and others, 1962) is bounded at its base by the Shattuck sandstone member of the Queen and at its top by the siliciclastic-dominated Yates Formation. The interfingering relationship with lower Capitan Reef carbonates (Silver and Todd, 1969) indicates a late Guadalupian age. On the Eastern Shelf the Seven Rivers is about 200 ft (61 m) thick and composed mainly of sandstone. Dominated by anhydrite on the Central Basin Platform, it is approximately 500 ft (152.4 m) thick. On the Northwest Shelf it is dominated by dolomite and anhydrite and is 650 to 1,000 ft (198.1–304.8 m) thick (West Texas Geological Society, 1976).

The Seven Rivers was described originally from exposures of limy shale and limestone and limestone breccia northwest of Carlsbad (Meinzer and others, 1926) but was redefined by Lang (1937) to exclude some of the uppermost part of the section. Mear and Yarbrough (1961) fixed the upper boundary at the base of the Yates Formation. It was recognized generally in the oil fields as the evaporite- and carbonate-dominated interval between the siliciclastic-rich Queen and Yates Formations.

Stratigraphic equivalents elsewhere in the Permian Basin include the lower part of the Altuda Formation in the Glass Mountains and the middle part of the Whitehorse Group in west-central Texas. It is capped by the Azotea Tongue, a bedded dolostone interval that is several hundred feet thick (West Texas Geological Society, 1976). In sequence stratigraphic terms, the Seven Rivers composes the shelf component of composite sequence CS-12 (Kerans and Kempter, 2002). According to field correlations that led to these sequence divisions, the Delaware Basin equivalent (Delaware Mountain Group) is the Pinery and Hegler members of the Bell Canyon Formation and the Manzanita member of the Cherry Canyon Formation. (fig. 2). Delaware Basin strata are discussed in greater detail elsewhere in this volume.

Subsurface Recognition and Correlation

The Seven Rivers Formation is recognized as an interval composed of thick carbonate and evaporite beds and subordinate siliciclastics that are overlain by thick sandstone beds of the Yates Formation and underlain by thick sandstone beds of the Queen Formation. In the absence of core, readily available gamma-ray logs are generally adequate for recognition and correlation of Artesia Group Formations. Seven Rivers carbonates and evaporites (anhydrite and halite) have significantly lower gamma-ray values than do the Queen and Yates subarkosic and arkosic siliciclastics. Correlations are facilitated by the laterally extensive tabular geometry of facies and by the basin-to-shelf facies tract structure whereby carbonate transitionally merges with stratigraphically equivalent evaporite. Rock-type recognition is facilitated in wells for which density, acoustic, or caliper logs are available. Carbonate- and anhydrite-dominated facies have higher bulk densities and acoustic interval transit times than do siliciclastic-dominated facies. Halite-dominated strata have low gamma-ray values coupled with very low densities and interval transit times. Caliper logs show that borehole enlargement in intervals of halite-bearing strata is present if halite-undersaturated, water-based fluid was used to drill the well and, in the absence of density or acoustic logs, provides a reliable basis from which to differentiate halite from carbonate and anhydrite in low-gamma-ray strata. Values of various geophysical well log responses from representative Upper Permian rock types are presented in the facies section of this chapter.

Tansill Formation

Stratigraphy, Type Section, and Regional Correlation

The Tansill Formation is in the Artesia Group (Tait and others, 1962) and is bounded at its base by the Yates Formation and at its top by the Salado Formation. The upper surface of the Tansill is considered to be the boundary between Guadalupian and Ochoan Series strata (for example, DeFord and Riggs, 1941). Thickness of the unit is approximately 125 ft (38.1 m) throughout its extent over much of the Permian Basin. It is as much as 350 ft (106.7 m) thick where it merges with the Capitan (West Texas Geological Society, 1976). DeFord and Riggs (1941) defined the formation and suggested that an outcrop 3.7 mi (6 km) along the Artesia-Carlsbad Highway from the Eddy County courthouse in Carlsbad be designated as the type section. At this location the Tansill is 123.5 ft (37.6 m) thick and composed of interbedded magnesium limestone and siliceous siltstone and sandstone. DeFord and Riggs (1941) also proposed recognition of the Ocotillo Member, a widespread 13.5-ft-thick (4.1-m) siliciclastic-dominated interval in the upper part of the formation that the authors claimed could be traced for more than 100 mi (160.9 km), although their cross section depicted only about 33 mi (53.1 km) of correlation distance across the Northwest Shelf between the type section and Halfway field in Lea County, New Mexico.

Stratigraphic equivalents of the Tansill elsewhere in the Permian Basin may include parts of the Tessey, Altuda, or Capitan Formations in the Glass Mountains. The upper part of the Yates, along with the overlying Tansill Formation, composes the upper part of the shelf component of a composite sequence (CS-14). Delaware Basin approximate equivalents of the Tansill include the Lamar carbonate member of the Bell Canyon Formation (Tyrrell, 1962; Kerans and Kempter, 2002), as well as several siliciclastic members (probably the Trap and Ramsey) that interfinger with the carbonates (fig. 2). However, Achauer (1971) argued (on the basis of his own fieldwork) that the Lamar merged with the upper part of the Capitan, not the Tansill. Kerans and Kempter (2002) correlated the Lamar in the Bell Canyon Formation with the lower half of the Tansill; however, the two intervals appear to be uncoupled by the intervening Capitan reef complex. Delaware Basin strata are discussed in greater detail elsewhere in this volume.

Subsurface Recognition and Correlation

The Tansill Formation is recognized as an interval composed largely of carbonate and evaporite that are overlain by thick evaporite of the Salado Formation and underlain by thick sandstone beds of the Yates Formation. The occurrence of anhydrite or halite in the basal interval of the Salado depends on position along the basin-to-shelf profile, with halite becoming more prevalent at greater distances from the reef zone. The top of the Yates has been recognized traditionally by presence of well-rounded, frosted, medium-grained sand (for example, Gester and Hawley, 1929). Such material, however, also occurs in the Queen and Seven Rivers and is probably more facies dependent than formation dependent.

The Tansill is recognized everywhere on the Permian Basin shelves and in the Midland Basin (DeFord and Riggs, 1941) and appears to be the uppermost unit that was deposited in the lee of the Capitan Reef. The laterally extensive Fletcher anhydrite unit overlies the Tansill and is considered to be the base of the Salado Formation. The extension of the Fletcher into the Delaware also marks the boundary between the Salado and the underlying, basin-limited Castile Formation. Tansill carbonate is primarily dolostone and is limited to a 10- to 25-mi-wide (16.1- to 40.2-km) zone in the immediate back-reef area on the Central Basin Platform and Northwest Shelf. Farther shelfward the Tansill is dominated by anhydrite and eventually subequal amounts of anhydrite and halite. The author has not identified a map that describes the mappable extent of the Fletcher unit; however, Page and Adams (1940) mapped the Tansill into Mitchell County on the Eastern Shelf, where it unconformably abuts Dockum Group strata. On their published cross section, Page and Adams (1940) considered the sulfate-dominated unit below halite (so-called "Upper Castile") and above the siliciclastic-dominated Yates to be the Tansill. In the Texas Panhandle the Tansill is thought to be indistinguishable from the Salado, where the composite section is dominated by halite and contains subordinate sulfate and siliciclastics. The upper part of the unit is variably truncated by halite dissolution (McGillis and Presley, 1981). Distribution of siliciclastics suggests east and northeast sources (McGillis and Presley, 1981).

In the absence of core, readily available gamma-ray logs are generally adequate for recognition and correlation of the Artesia Group. Tansill carbonates and evaporites (anhydrite and halite) have significantly lower gamma-ray values than do the underlying Yates K-feldspar-bearing siliciclastics (fig. 12). As briefly noted earlier in the Yates section, however, a correlation problem arises locally when only a gamma-ray log is available for picking the boundary between the Yates and Tansill Formations. Locally the Tansill contains numerous uranium-bearing dolomite and magnesite intervals that can be misinterpreted as siltstone beds (Garber and others, 1989). Acoustic or density logs facilitate an appropriate rock-type-based interpretation, however, because siltstone density is diagnostically lower than that of the relatively dense dolomite that composes most Tansill carbonate.

Correlations are further facilitated by the laterally extensive, tabular geometry of facies and by the shelf-to-basin facies tract whereby carbonate laterally transitions to evaporite. Tansill rock-type recognition is facilitated in wells for which density, acoustic, or caliper logs are available. Carbonate- and anhydrite-dominated facies have higher bulk densities, lower density porosities (fig. 12), and lower acoustic-interval transit times than do siliciclastic-dominated facies. Halite-dominated strata have low gamma-ray values coupled with very low densities and interval transit times. Caliper logs show borehole enlargement in intervals of poorly cemented siliciclastics, as well as in intervals of halite-bearing strata if halite-undersaturated, water-based fluid was used to drill the well.

Artesia Group Diagenesis

Diagenetic processes that have affected the Artesia Group include marine and meteoric phreatic cementation, meteoric vadose, dolomitization, dolomite cementation, dehydration of gypsum to anhydrite, replacement of carbonates by sulfates, replacement of sulfates by carbonates, evaporite dissolution, dissolution of feldspar and carbonate grains (creating secondary porosity), and clay and feldspar authigenesis (dissecting and obliterating porosity). The importance at any location of any specific control or combination of controls is determined by the presence of specific depositional facies. Examples include replacement of carbonate by sulfate that was facilitated in rocks where sulfate-oversaturated brine (indicated currently by abundant anhydrite) overlay carbonate (fig. 21); secondary-porosity development after feldspar dissolution and clay authigenesis is pronounced in arkoses and subarkoses; and pel- or fossil-moldic secondary porosity is most pronounced in grain-rich carbonate.

Lucia (1961) performed some of the early investigations of Tansill diagenesis. He noted occurrences of lacy calcite crystals with included dolomite. The crystal form of anhydrite is outlined by the distribution of inclusions, suggesting that calcite has replaced anhydrite.

Replacement of dolomite by calcite is suggested by the decrease in number of dolomite inclusions toward the edge of the calcite crystals.

Parsley and Warren (1989) described diagenetic characteristics in the Tansill from Dark Canyon that might be similar to those of Tansill intervals that are situated in similar paleo-geographical settings elsewhere on shelves surrounding the Delaware Basin. They observed isopachous bladed and subsequent high-Mg calcite and aragonitic cements in samples from the outer shelf, whereas in the barrier samples, they observed parallel-fibrous and botryoidal-fibrous aragonite in sheet cracks. Geopetal cements in crossbedded and pisolite grainstones indicated vadose diagenetic conditions. Local terra rosa fills in tepee sheet cracks indicated some dissolution and accumulations of insoluble residue. Dolomitization was pervasive. Stable isotope ($\delta^{13}C$ and $\delta^{18}O$) data indicated that dolomitizing fluids were evaporated almost to calcium sulfate saturation and thus suggested their formation in penecontemporaneous evaporative lagoons. Occurrences of pseudomorphs after evaporites suggested previous pore filling by evaporites. Zoned luminescence in calcite spar indicated at least two episodes of meteoric diagenesis, which promoted replacement and removal of evaporite cement, as well as neomorphism of aragonite and high-Mg calcite. Meteoric dissolution of skeletal material also promoted secondary porosity development.

Mazzullo (1999) noted that marine cements in the Tansill are dominated by prismatic calcites with microdolomite inclusions and some radiaxial-fibrous form that he interpreted as former high-Mg calcite. The $\delta^{18}O$ and $\delta^{13}C$ compositions of the least-altered cements (–1.6‰ and 5.8‰ PDB, respectively) suggest that precipitation was from marine pore fluid. Original aragonitic cement with similar isotopic composition is volumetrically minor. In contrast, former aragonite marine cement dominates in coeval platform-margin patch reefs, the Capitan reef, and in shelf-crest pisolites. Mean $\delta^{18}O$ composition of the dolomite that replaced peritidal deposits (0.1‰ PDB) suggests that it precipitated from marine fluids of elevated salinity. Stabilization of earlier diagenetic phases most likely attended precipitation of equant calcites in the rocks, which is interpreted to have occurred in a subsequent meteoric phreatic system. A second generation of equant cements precipitated still later in a deeper, meteoric-dominated system. Replacement by poikilotopic calcite of syndepositional evaporites is the most recent diagenetic phase and appears to have accompanied meteoric dolomite calcification during the Tertiary, according to stable, oxygen-carbon isotope data.

Mazzullo (1999) suggested that abundant marine cementation in Tansill rocks may have been promoted by seawater pumping through the sediments on a wide, shallow shelf. Microbial activity in the grainstones may have been promoted by restricted circulation around associated peritidal islands. In contrast, dominantly micritic cements in the late highstand facies of Tansill sequences were suggested to mark more restricted environments in terms of shelf width and energy.

Examples of feldspar dissolution, along with feldspar and clay authigenesis, were documented by Spencer (1987) in Queen sandstone from Yates field, southeastern Central Basin Platform. Here the three processes occur in the same 1-ft (0.3-m) cored interval, suggesting that deposition of feldspar and kaolin cement in some pores was accompanied by production of secondary porosity elsewhere. Spencer (1987) cited Dunham (1972) to suggest that these processes probably record vadose meteoric diagenesis.

Controls on Porosity and Permeability

Interparticle porosity and moldic porosity that formed by feldspar dissolution provide the primary reservoirs for hydrocarbon accumulations in Upper Guadalupian siliciclastic strata. Siliciclastic interparticle porosity is optimized by the well-sorted textures where fine-grained material is generally absent to plug pore throats formed between fine- to very fine grained sand particles. In some cases dissolution of cements enhanced interparticle porosity (for example, in the Queen at Concho Bluff; Mazzullo and others, 1992). Plugging of porosity by evaporites (for example, in the Yates at North Ward-Estes; Borer and Harris, 1991) and changes to finer grained facies (for example, in the Queen at Concho Bluff; Mazzullo and others, 1992) provide the updip seals for most Guadalupian siliciclastic reservoirs. Tansill reservoirs produce mainly from shelf carbonate strata; therefore, the appropriate outcrop analogs are located in the back-reef shelf, downslope of evaporite settings. Parsley and Warren (1989) observed that interparticle and intraskeletal porosity are the dominant porosity modes in Tansill carbonates from Dark Canyon. Original porosity as high as 45 percent has been reduced by cement to an average of 7 percent, with local occurrences as high as 17 percent. Well-sorted skeletal-peloid grainstones show the most consistency in porosity values that the writers described as comprising strike-aligned lenses that fringe barrier islands. Brister and Ulmer-Scholle (2000) described interparticle porosity in Seven Rivers dolomite reservoir facies from the Grayburg Jackson Pool (Northwest Shelf, Eddy

County, New Mexico). They interpreted productive interparticle porosity as resulting from deposition in tidal channels, judging from the geographic pattern of their pore-volume (neutron-$\phi \times$ thickness) map (fig. 22).

DEPOSITIONAL SETTING AND GEOGRAPHIC VARIATIONS IN FACIES DISTRIBUTIONS

Artesia Group facies are, by definition, endemic to the back-reef shelf of the Guadalupian reef complex. Biota is relatively scarce in areas shelfward of the immediate back-reef zone, and carbonate sediment texture becomes progressively more fine grained, suggesting that marine circulation in more shelfward positions was restricted and was prone to above-normal marine salinity (Garber and others, 1989). Evaporite precipitation occurred within a few hundred meters of marine- to near-marine carbonate depositional environments (Sarg, 1981) and occurred in the lee of shoals, suggesting evaporative lagoon conditions. Farther shelfward (6–8 mi of the pisolitic shelf crest; Garber and others, 1989), evaporites were deposited in salinas and sabkhas. In many sandstone intervals, textures were well to very well sorted, and sediment color is red. Silt- and clay-sized sediment is observed in some intervals; therefore, its absence in well-sorted sandstone intervals suggests sorting processes that finely discriminate among available particle sizes. These are characteristics that suggest arid conditions where sand grains were sorted by eolian processes. Finer grained, more poorly sorted sediments are often contained in halite-bearing intervals or halite-dissolution residue or are in stratigraphic contact with carbonate mudstone. Thus, finer grained siliciclastics were probably trapped in ephemeral ponds, on sabkhas, and in lagoons.

The abundance of siliciclastics in the Queen and Yates Formations probably indicates deposition during periods of relative sea-level lowstand, compared with the other Guadalupian formations (for example, Borer and Harris, 1991). Additionally, uplift in siliciclastic source areas and climatic changes could have influenced siliciclastic depositional patterns.

It is well documented that Upper Guadalupian depositional facies are systematically distributed along depositional slope. The distribution of depositional facies is also controlled by phase of sea-level change; that is, facies distributions vary between highstand, lowstand, and transgressive stages. A good summary of ideal depositional patterns in the context of sea-level phase was given by Andreason (1992) (fig. 23). During sea-level highstand, carbonate facies dominate basinward of the shoreface area. The most grain-rich depositional facies are in the immediate back-reef area basinward of and including the pisolite-shoal zone. Lagoonal areas are characterized by wackestone and mudstone, and algal-laminated carbonates are typical of tidal flats. Farther shelfward, shoreface then sabkha and associated brine pools occur. In formation or subformation-scale intervals (for example, Queen, lower Seven Rivers, and Yates) that contain prominent siliciclastic-dominated strata, siliciclastics may also compose a significant fraction of otherwise carbonate- or evaporite-dominated facies.

Facies tract profile depends on the phase of the relative sea-level transition (Andreason, 1992). During fall of sea level, evaporitic-inner-shelf and siliciclastic-dominated depositional environments migrate basinward, siliciclastics may be deposited in previously carbonate or evaporite dominated lagoons, and eolian environments may extend to the shelf margin. Eolian siliciclastics deposited during lowstand were reworked during transgressions into broad sand sheets that occur over large areas of the shelf prior to establishment of carbonate depositional environments during subsequent sea-level highstand.

SEQUENCE STRATIGRAPHY OF THE ARTESIA GROUP

Sequence stratigraphy is a method of interpreting stratigraphic development within the context of relative sea-level change. A stratigraphic sequence is an unconformity-bounded package of genetically related strata deposited during a single cycle of sea-level rise and fall, where unconformities record periods of sea-level lowstand. No cycle order (length or time scale) is implicit in the definition of a sequence; however, the most readily recognized unconformities (sequence boundaries) are regionally extensive and record prolonged erosion on the shelf and coastal plain during sea-level falls of relatively high magnitudes. Cyclic strata (parasequences or high-frequency cycles) within sequences record deposition during higher frequency, relative sea-level rises and falls of lower magnitude than those that promote unconformity development. High-frequency cycles are organized into coeval sedimentary facies, or system tracts, that record lateral distribution of depositional environments. System tracts include those deposited during sea-level lowstands (LST), transgressions (TST), and highstands (HST). Sequence boundaries, submarine fans, and lowstand wedges develop within the LST. Marine flooding surfaces (transgressive and maximum flooding surfaces) and onlapping high-frequency cycles on the shelf are indicative of the TST. Sedimentary aggradation on the shelf and progradation of shelf facies tracts are indicative of the HST.

Variations in stratal thickness are limited by accommodation space or the volume available for accumulation of sediment. Accommodation is greatest during sea-level highstands and lowest or absent during lowstands. Changes in local sea level result from combinations of eustatic and local to regional tectonic (uplift and subsidence) processes. Glacio-eustatic cycles are fairly well documented for more recent Earth history and for certain periods during late Precambrian, Late Ordovician, Pennsylvanian, and mid-Permian time. Similarly, most agree that worldwide cyclic depositional signals were controlled by late Cenozoic glacial cycles. However, little evidence of glaciations has been recognized for many other periods for which sea-level related cyclic geologic sections are abundant. The Late Permian is a time of abounding cyclic deposition for which significant glacial features have not been recognized. Nonetheless, orbitally forced climatic models are often evoked to tentatively date depositional-cycle periodicity throughout the Permian record (for example, for the Yates in the Permian Basin; Borer and Harris, 1991). Increases in seafloor spreading rates and ridge lengths are also hypothesized to potentially produce the magnitudes of sea-level variation interpreted from the geologic record. Different processes are conjectured to produce cycles of different periodicities. Hallam (1992) provided a good summary of issues and theories concerning sea-level change and the geologic record.

Two general sequence stratigraphic models are popular today: one developed at Exxon that systematically groups strata between unconformities or hiatal surfaces developed during sea-level lowstands (Vail and others, 1977) and another that groups strata between widespread maximum flooding surfaces (Galloway, 1989). The Exxon approach has been most commonly used in the Permian Basin. It is particularly viable there because a large part of the stratigraphic section includes carbonates upon which erosional unconformities (type 1 sequence boundaries) are frequently recognized. The Galloway model has been used extensively on the Gulf Coast, where siliciclastics are the most abundant sediment type and unconformities are generally difficult to recognize.

So-called third-order (Vail and others, 1977) or composite (Kerans and Kempter, 2002) sequence boundaries are at the approximate vertical scale of formations. However, sequence boundaries are not necessarily reflected in historically recognized formation boundaries. For example, in the outcrop-based (Guadalupe Mountains) analysis of Kerans and Kempter (2002), boundaries between the Queen and Seven Rivers Formations, between the Seven Rivers and Yates Formations, and between the Tansill and Salado Formations are also boundaries between composite sequences. However, another sequence boundary divides the Yates into lower and upper parts. The lower Yates composes a single composite sequence (CS-13), whereas the upper Yates and the Tansill Formations compose CS-14 (fig. 2).

Higher order (presumably fourth- and fifth-order) cycles compose composite sequences. At this level of resolution, Kerans and Kempter (2002) divided the Queen into two sequences (Q1, Q2), the Seven Rivers into four sequences (Sr1-4), the Yates into five sequences (Y1-6), and the Tansill into two sequences (T1, T2). Mazzullo's analysis (1999) of the Tansill exposure in Dark Canyon (Guadalupe Mountains) demonstrates how sequences are identified. Two sequences were recognized by Mazzullo (1999) in the Tansill section on the basis of biotic diversity, parasequence thickness, and facies-stacking patterns. The boundary between them was suggested to be at or near the base of the Ocotillo Member (fig. 2). Maximum flooding of the platform occurred during deposition of sequence 1 in the lower part of the middle Tansill. Environments were biostromes, mainly high-energy, shallow subtidal packstones and grainstones and associated peritidal islands in the early highstand system tract in this sequence.

Borer and Harris (1991) suggested that the Yates Formation on the Northwest Shelf and Central Basin Platform composed one third-order sequence that encompassed as many as 22 high-frequency (fifth-order) cycles bundled into five lower (fourth-) order cycles. They suggested that the Yates was deposited over 1.5 to 2 m.y. and that depositional cyclicity reflected orbitally forced sea-level or climatic variations of 100- and 400-ky periodicity (orbital eccentricity cycles in Milankovitch climate theory). In the view of Borer and Harris (1991), the lower part of the Yates records a third-order sea-level rise and the upper part records a third-order sea-level fall. The magnitude of fourth- and fifth-order sea-level oscillation affected the relative prominence of carbonate, evaporite, and siliciclastic facies; third-order sea-level rise produced a greater abundance of carbonate in the lower part of the Yates, whereas third-order sea-level fall produced proportionally more siliciclastic facies in the upper part (Borer and Harris, 1991). Vertical trends of cycle thickness are also affected. Thicknesses might be expected to decrease in sequential sedimentary cycles (fig. 20) because higher-order cyclic accommodation volumes at any given location are progressively reduced overall during the third-order sea-level fall. Cycle boundaries may be difficult to recognize in units where sequence boundaries occur within siliciclastic intervals, however, and the result may be apparent deviations from the upward pattern of cycle thinning. Occurrences of intraclasts in siliciclastic intervals may be at sequence boundaries, on maximum flooding (ravinement) surfaces (as interpreted for fig. 24), or they may simply be channel deposits within a cycle. The example in figure 24 is interpreted as a ravinement surface because it is near the top of a siliciclastic interval (TST) that underlies a carbonate interpreted as part of the HST.

It is noteworthy that Kerans and Kempter (2002) interpreted the Yates in the Guadalupe Mountains to contain a third-order (composite) sequence boundary within the formation (fig. 2).

STRUCTURE OF THE ARTESIA GROUP AND CONTROLS OF INTERVAL THICKNESS

Formation isopach maps show similar regional thickness distributions for all Artesia Formations and reflect the regional structural configuration of the Permian Basin. Units thin from the Midland Basin onto its northern and eastern shelves and onto the Central Basin Platform. On the Northwest Shelf, units are thickest in the near-back-reef zone and thin onto the platform. Rates of shelfward unit thinning are greater along the west edge of the Central Basin Platform than on the Northwest Shelf, probably because of a steeper shelf-to-basin profile that was maintained along the margin of the Central Basin Platform (Borer and Harris, 1991). Ranges of formation thickness are noted in the sections for each formation.

Structural patterns are similar for all Artesia Group formations. The primary structural element is the down-to-the-basin dip of strata that is the primary control on migration of hydrocarbons from basinal source beds into reservoirs that are developed on the surrounding shelves. Field-scale structures are common to most fields and reflect deep-seated structural elements that are reflected on pre-Permian surfaces. Documented examples of stratigraphically persistent field-scale structures include Keystone field in Winkler County, where Guadalupian-productive anticlinal structure can be mapped on horizons as deep as the top of the Ellenburger, where it is interpreted as a faulted anticline (fig. 25) (Galloway and others, 1983). North Ward-Estes (Ward County) resides on a north-northwest-trending anticline located along the west margin of the Central Basin Platform in Ward County, which can be mapped for more than 13 mi (21 km) (fig. 26). Means field on the northeast edge of the Central Basin Platform in Andrews

County contains two domal anticlines (fig. 27) (Price and others, 2000). At Yates field in Pecos County the geometry of the southeast corner of the Central Basin Platform is reflected in Guadalupian stratal structure (fig. 28) (Craig, 1988). Concho Bluff and North Concho Bluff fields are located on two anticlinal noses on the east-central edge of the Central Basin Platform in Crane, Ector, and Upton Counties (Mazzullo and others, 1992) (fig. 29). The McFarland-Magutex field area is developed on an anticlinal nose on the northeast edge of the Central Basin Platform (fig. 30) (Holtz, 1993). The stratigraphic persistence of structures and apparent syntectonic deposition in Upper Guadalupian units suggest that tectonic movement of structural elements continued throughout the Late Permian.

Smaller-scale structures are present in some fields that are limited to various Permian horizons. These are most likely to reflect local carbonate or evaporite dissolution episodes. Two notable examples occur in Yates field and North Ward-Estes field. At Yates field the top of the San Andres was heavily karsted during emergence of the San Andres platform, thus creating topography that is reflected in overlying Grayburg, Queen, and Seven Rivers horizons (fig. 28B) (Craig, 1988). In places more stratigraphically limited, effects may be observed. In North Ward-Estes, Andreason (1992) mapped locally thinned areas (fig. 31) that he interpreted on the basis of observations of brecciated intervals in core, as resulting from sulfate dissolution. An isopach map of the overlying sandstone interval (discussed briefly later) indicates local structural depressions in the karst-affected area.

Control of interval thickness by field-scale structure has been documented. Productive Queen Colby sandstone units in Keystone field pinch out onto an anticline within the field, thus suggesting structure-controlled sand accumulation (fig. 25D) (Major and Ye, 1992, 1997). Concho Bluff and North Concho Bluff fields (discussed briefly earlier) are marked by thinning of evaporites onto anticlinal noses (fig. 29D). A stronger case can be made for thinning of siliciclastic units onto the main structure in the center of the field (fig. 29C). At Means field, west of and adjacent to McFarland field, cross sections of Queen sandstone show thinning of sandstone intervals onto the structural domes (Galloway and others, 1983). At North Ward-Estes field Andreason (1992) observed that locations of sulfate-dissolution thinning of one dolomite-bearing interval coincide with thickening in the overlying siliciclastic-dominated interval (fig. 31), thus establishing relative timing of the dissolution event and deposition of the Strays unit. Karsting of the emergent San Andres surface at Yates field modified structure-influenced topography that affected thickness distributions in several overlying units (fig. 28B, C, D) (Spencer, 1987; Craig, 1988). The effect can be observed in individual facies as well. For example, thickness trends of the basal Seven Rivers anhydrite interval (fig. 28D) (Spencer, 1987) mimic those of the Grayburg and Queen Formations, which themselves show thickness relationships to the topography developed by dissolution on the top of the San Andres (fig. 28B) (Craig, 1988).

RESERVOIR DEVELOPMENT

Most middle and upper Artesia Group platform oil reservoirs are assigned to either the Queen Tidal-Flat Sandstone (eastern side of the Central Basin Platform) or Artesia Platform Sandstone Play (west side of the Central Basin Platform) (Dutton and others, 2005). These reservoirs are mainly productive from siliciclastics of the Queen and Yates Formations, although Seven Rivers sandstone also contributes in many fields. Dolostones of the Queen, Seven Rivers, Yates, and Tansill Formations form secondary reservoirs. Production from the dolostones is generally commingled with production from sandstone reservoirs.

Not all reservoirs for which plays are named (for example, Grayburg High-Energy Platform Carbonate—Ozona Arch Play) produce only in those plays. For example, Farmer field (Grayburg High-Energy Platform Carbonate—Ozona Arch Play) also produces from the lower Queen (Bebout, 1994). Similarly, the main reservoir at Shafter Lake (Queen Tidal-Flat Sandstone Play) is the Yates (Dutton and others, 2005). According to Dutton and others (2005), 94 reservoirs had produced more than 2,035 MMbbl of oil from the two Upper Permian sandstone plays through 2002. Many of these fields produce from multiple Artesia Group formations (including Grayburg carbonate), and a few include San Andres carbonate. Production from these other reservoirs is included in cumulative production figures.

Yates reservoirs are especially noted for gas production and are classified in the Upper Guadalupian Platform Sandstone Play (Kosters and others, 1989). In a survey of Texas fields whose reservoir name specified Yates as the primary productive interval, 1,295 wells were listed as producing from 88 reservoirs. Of these wells, 69 percent are classified as gas producers (Railroad Commission of Texas, 2003).

Reservoir Distribution

Hydrocarbon production from upper Guadalupian shelf strata largely occurs from Northwest Shelf and Central Basin Platform carbonate and siltstone that lie between the Goat

Seep/Capitan reefs and evaporitic lagoons (Ward and others, 1986; Dutton and others, 2005). A few more occur on the Northern Shelf, Ozona Arch, and Eastern Shelf. They are positioned in shelf-margin-aligned belts generally upslope of the carbonate depositional environments that mark the shelf margins during sea-level highstands.

More than one Artesia Group formation may be productive in some fields. It is common for either or both the Seven Rivers and Tansill to provide secondary production in a field where the Yates is the primary reservoir. North Ward-Estes field on the west margin of the Central Basin Platform, for example, produces from both the Yates and Seven Rivers Formations (Ward and others, 1986). Generally, productive reservoirs are at progressively higher stratigraphic positions as the platform is traversed from east to west toward the Delaware Basin or north to south on the Northwest Shelf, reflecting the progradational character of the Artesia Group (Ward and others, 1986).

Trapping Mechanisms

Most Upper Permian hydrocarbon shelf reservoirs are developed in porous sandstone and siltstone (mainly in the Queen and Yates Formations, but also in the Seven Rivers sandstone locally) that were deposited on the back-reef middle shelf. Porous carbonate, especially the Tansill (Ward and others, 1986) forms secondary reservoirs locally, although more often carbonate is relatively impermeable and forms sandstone-reservoir top seals. Reservoirs are plugged along their updip extents by impermeable evaporites, mainly anhydrite. Evaporite and impermeable carbonate form reservoir-specific top seals over large areas. Regionally extensive Salado evaporites, where still present following regionwide dissolution of upper parts of the interval, provide a basinwide top seal (Hills, 1984). Source beds are most probably organic-rich deposits in the adjacent basinal areas, especially the Delaware Basin (Hills, 1984).

The basinward dip of reservoir strata provides the primary structural control on hydrocarbon migration and accumulation. Field-specific focusing of hydrocarbon migration and entrapment for shelf units is provided by anticlines. Prominent examples include the Keystone Colby reservoir that formed over a deep-seated faulted anticline on the west margin of the Central Basin Platform in Winkler County (fig. 25) (Galloway and others, 1983; Ward and others, 1986; Major and Ye, 1992, 1997); North Ward-Estes field that formed over a strike-elongate anticline on the west flank of the Central Basin Platform in Ward County (fig. 26) (Ring and Smith, 1995); Means field that formed over two north-south-aligned domes on the northeast margin of the Central Basin Platform in Andrews County (fig. 27) (Price and others, 2000); Yates field that formed over an apparently folded, U-shaped anticline in Pecos County (fig. 28); and Concho Bluff and Concho Bluff North, located over structural noses (fig. 29) in Upton, Crane, and Ector Counties, and McFarland Queen reservoir, which formed over an east-dipping structural nose on the northeast margin of the Central Basin Platform in Andrews County (fig. 30) (Holtz, 1993).

The following summary of Artesia reservoirs in Texas is based on a Railroad Commission of Texas Annual Report (2003) list of reservoirs for which entries designate a specific reservoir in the field name (table 2). There are at least 41 Queen reservoirs, all located on the Central Basin Platform; at least 7 Seven Rivers reservoirs located on the Central Basin Platform and 1 on the Eastern Shelf; at least 72 Yates reservoirs located on the Central Basin Platform, 11 on the Northern Shelf (east and northeast of Seminole), 2 on the Eastern Shelf, and 3 on the Ozona Arch in the south part of the Midland Basin; and at least 9 Tansill reservoirs, all on the Central Basin Platform in Pecos County, Texas. Comprehensive data on all Artesia Group reservoirs on the Northwest Shelf in New Mexico were unavailable for this report. Of the larger reservoirs (cumulative production >1 MMbbl), however, 24 are in the Queen, 18 are in the Seven Rivers, 15 are in the Yates, and 1 is in the Tansill (Dutton and others, 2005).

Table 2. Numbers of Upper Guadalupian reservoirs in Texas and New Mexico, sorted by reservoir. Texas values were summarized by the author from the annual report of the Railroad Commission of Texas (2003); New Mexico values are from Dutton and others (2005).

Texas reservoir	**CBP**	**E Shelf**	**N Shelf**	**Ozona Arch**	**Reservoir total**
Queen	41	0	0	0	41
Seven Rivers	7	1	0	0	8
Yates	72	2	11	3	88
Tansill	9	0	0	0	9
Total					**146**
NM reservoir	**NW Shelf**				
Queen	24*				
Seven Rivers	18*				
Yates	15*				
Tansill	1*				
Total					**16***

*Cumprod >1 MMbbl

Reservoir Examples

The McFarland Queen reservoir (fig. 30) in Andrews County, the most productive field in the Queen Tidal-Flat Sandstone Play, produces from two sandstones in the lower Queen Formation (fig. 30B) (Tyler and others, 1991; Holtz, 1994). The sandstones, which form the bases of progradational, upward-shoaling cycles, were deposited in intertidal-flat tidal-channel, and shoreface environments. They are overlain by supratidal dolomudstones and massive anhydrite at the top (Holtz, 1994). Production is highest where the sandstones are thickest, in areas interpreted to be tidal-channel deposits. Porosity ranges from 11 to 24 percent and averages 12 percent; permeability ranges from 3 to 24 md (3 to 24 × 10–3 μm^2) and averages 12 md (12 × 10–3 μm^2) (Holtz, 1994). A structural nose focused hydrocarbon migration into the field (fig. 30A).

The North Ward-Estes reservoir (fig. 32) in Ward County, the most productive field in the Artesia Platform Sandstone Play, produces from the Yates, Queen, and Seven Rivers Formations (Andreason, 1992; Eide and Mazzullo, 1993; Bain, 1994; Mazzullo and others, 1996). Most of the production is from nine very fine grained sandstone and siltstone reservoirs in the Yates Formation that are interbedded with low-permeability dolomite seals (Ring and Smith, 1995; 13B; table 1). The sandstone reservoirs comprise marine-reworked-eolian or late-highstand-lagoonal siliciclastic components of fifth-order depositional sequences. Hydrocarbon migration was focused into a strike-elongate anticline that lies at the crest of a basinward-dipping structural monocline.

The reservoir interval at Concho Bluff and North Concho Bluff fields is on the east edge of the Central Basin Platform in Crane and Upton Counties and consists of several sandstone beds that are interbedded with thin anhydrite and salt in the upper Queen Formation (Mazzullo and others, 1992; Lufholm and others, 1996) (fig. 29). The depositional setting was a broad, low-relief shelf where lowstand fluvial and associated clastics interfingered with highstand evaporite deposits. Mazzullo and others (1992) argued that the siliciclastics are marked by little, if any, marine reworking. Permeability in the reservoir sandstones ranges from 1 to 1,200 md (1 to 1,200 × 10–3 μm^2) and averages 70 md (70 × 10–3 μm^2); porosity ranges from 9 to 26 percent and averages 16 percent (Mazzullo and others, 1992). Structural position and porosity distribution, rather than net sandstone thickness, are the primary controls on production at Concho Bluff and North Concho Bluff fields (fig. 29).

The Keystone Colby reservoir, located on the northwest edge of the Central Basin Platform (Winkler County), encompasses 16 mi^2 and comprises five productive, massive, arkosic sandstone intervals (fig. 25) that are interbedded with nonproductive, low-porosity dolomite and anhydritic dolomite (Major and Ye, 1992, 1997). Colby reservoir rocks are interpreted as having been deposited in a lagoonal setting behind a carbonate-rimmed bank margin in a series of upward-shoaling cycles composed of sandstone and dolomite. During sea-level highstands, the lagoon was flooded, and carbonate sediments were deposited. During sea-level lowstands, the lagoonal carbonate sediments probably were exposed and subjected to karst processes (Major and Ye, 1992, 1997). As sea level rose again, windblown sand was deposited in marine and peritidal environments in the lagoon. The most porous sandstones are interpreted as having been deposited in relatively shallow marine water (Major and Ye, 1992, 1997).

Opportunities for Additional Resource Recovery

For the Queen Tidal-Flat and Artesia Platform sandstone plays, remaining reserves are estimated to be 69 MMbbl (Dutton and others, 2005). The Upper Guadalupian Plays in the Permian Basin are in a mature stage of development, and few new fields have been discovered recently (Dutton and others, 2005). For example, Yates reservoir discovery peaked in the 1970's (fig. 33A), annual gas and oil production rates are in steep decline (fig. 33B), and many fields have been in EOR for some time. Even the most optimistic forecasts suggest that Yates gas production will decline to 50 percent of present rates by 2025 (fig. 33C) (Combs and others, 2003). Recovery efficiencies range from 29 to 47 percent, with the high value coming from North Ward-Estes; however, most fields average about 30 percent (Galloway and others, 1983).

Some fields have been in waterflood since the 1960's. For example, Means field initiated waterflooding in late 1961; daily oil production increased sixfold over the next year and ninefold over 4 years. Two Upper Guadalupian reservoirs (at Yates and North Ward-Estes fields) have been flooded with CO_2 (Mark Holtz, personal communication), and CO_2 injection may become more economically viable in the future. Traditional application of field extension and infill drilling methods will also play a role in continued production from Upper Guadalupian reservoirs, as well as development of secondary or tertiary reservoirs that were not economically viable in the past. In some cases productive intervals may have been bypassed in wells drilled to deeper targets. Sandstone porosity ranges from 6 to 19 percent. Major and Ye (1992, 1997) noted that several thick, potentially productive sandstone units in Keystone Colby field are not open to many well bores.

OCHOAN SERIES ON THE PERMIAN BASIN SHELF

The Ochoan in the Permian Basin contains no hydrocarbon reservoirs on the shelf, although basal Ochoan evaporites form the ultimate top seal for underlying Guadalupian reservoirs. Therefore, the following discussion will be introductory and brief. Superposition of the Salado Formation evaporites on the top of the Guadalupian Series (fig. 2) effectively inhibits hydrocarbon migration into Ochoan units, and lack of a seal above the Ochoan precludes widespread entrapment within the interval of hydrocarbons that may have been generated within the series. Drilling through the Ochoan to deeper reservoirs in the immediate vicinity of the WIPP salt-hosted nuclear-waste repository in Eddy County (near Carlsbad, New Mexico) is prohibited because of potential compromise of seal integrity at the site.

Units that compose the Ochoan Series on the shelf and Midland Basin include, from oldest to youngest, the Salado, Rustler, and Dewey Lake Formations. The Salado is locally more than 2,800 ft (853 m) thick and was named by Lang (1935) for a halite-rich interval that he originally designated in 1923 as the upper part of the Castile Formation. The upper Castile unit was differentiated from the lower part (still called Castile) by overall color, shale content, and K_2O concentration. The older terminology continued to be used for a while thereafter (for example, Page and Adams, 1940). The Castile of present usage is restricted to the Delaware Basin (Adams, 1944) and will not be discussed further here except to indicate that it is considered to be the top seal for Delaware Basin hydrocarbon reservoirs and ultimately responsible for controlling migration of hydrocarbons from basinal source beds into reservoirs on the surrounding shelves (Hills, 1984). The Rustler is locally more than 500 ft (152 m) thick and was named by Richardson (1904) for an incomplete section of magnesian limestone and siliciclastics that overlies the Castile Gypsum (currently called Salado) in Culberson County. A description of a complete subsurface section was provided by Adams (1944) that included stratigraphically and geographically varying intervals of dolomite, evaporites, and clastics. The Dewey Lake Formation, locally more than 350 ft (107 m) thick, was named by Page and Adams (1940) and further described by Giesey and Fulk (1941) for redbeds and minor gypsum that overlie the Rustler and underlie Triassic redbeds in the Midland Basin. Miller (1966) recognized the Pierce Canyon Formation in the Delaware Basin as equivalent to the Dewey Lake. The Dewey Lake/Pierce Canyon and stratigraphically younger but superficially similar Triassic redbeds are distinguished locally by mineralogic similarity of the Dewey Lake/Pierce Canyon to underlying Upper Permian siliciclastics; occurrence of anhydrite cement in the Permian interval; deeper red color, higher gypsum content, and wider textural range in the basal Triassic beds; and a zone of bleaching at the interpreted Permian-Triassic unconformity.

Most interest concerning the Ochoan has been related to the role of the Salado (1) as a potash resource (for example, Udden, 1915; Schaller and Henderson, 1932; Lang, 1942; Jones, 1954, 1972; Adams, 1969; Hiss, 1976; Cheeseman, 1978; Lowenstein, 1982, 1988; Bachman, 1984; Harville and Fritz, 1986; Holt and Powers, 1987; Stein and Krumhansl, 1988; and Barker, 1993, 1999); (2) as a nuclear-waster repository (for example, the more recent include Brookins,1990; Stormont, 1990; Milligan, 1991; Chaturvedi, 1996; Borns, 1997; Hurtado, 1997; Weart, 1997; Holt, 1999; Beauheim, 2002; Snow, 2002; Powers and others 2003; and Brush, 2004), and (3) because Salado halite dissolution may underpin topographic development and surface-water salinization in the region, especially in the High Plains (for example, Johnson, 1901; Baker, 1915; Gustavson and others, 1985; Baumgardner and others, 1982; Goldstein and Collins, 1984; Gustavson and Finley, 1985; and Dutton, 1987, among others).

Steiner (2001) used the Dewey Lake and Rustler Formations for magnetostratigraphic analyses, and Fracasso and Kolker (1985) and Kolker and Fracasso (1985) dated Dewey Lake (Midland Basin and Texas Panhandle) volcanic ash to determine absolute ages for part of the Upper Permian section. Miller performed the most comprehensive analysis of the Pierce Canyon (apparent Dewey Lake equivalent in the Delaware Basin), where he described petrographic affinities to other Upper Permian siliciclastic intervals in the region and developed criteria for distinguishing the Pierce Canyon from overlying Triassic strata of similar appearance. Several theses and dissertations have dealt with the Ochoan evaporites, including Snider (1966) and Hovorka (1990).

SUMMARY AND CONCLUSIONS

The Artesia Group of the Permian Basin comprises a diverse assemblage of carbonate, evaporite, and siliciclastic facies that occur in stratigraphically cyclic packages and record deposition in marginal marine and terrestrial environments in a region characterized by climatic aridity. Gamma-ray logs can be used readily to differentiate pure carbonate, anhydrite, and halite facies from sandstone facies, wherein siliciclastics are notably more radioactive because they contain abundant potassium in the form of K-feldspar and K-bearing clay. Differentiation of halite from anhydrite and dense carbonate is significantly facilitated by availability of density, acoustic, and caliper logs. The Artesia Group consists of two broad paleo-geographic realms: (1) back-reef, shallow subtidal, intertidal, and peritidal environments and (2) terrestrial evaporitic, fluvial, and eolian environments. In near-reef areas on the shelf, sea-level lowstand terrestrial deposits are largely reworked by transgressive marine processes, whereas original terrestrial character may be preserved in areas farther shelfward. Interval thicknesses are controlled mainly by accommodation volumes that reflect relative sea-level changes; however, preexisting topography that reflects either or both deep-rooted structural movements and erosional processes locally affects unit thickness and facies distributions. Patterns of stratigraphic cyclicity record systematic variations in sediment accommodation volumes, salinity, and siliciclastic sediment supply; however, the relative importance of controls by eustatic sea level, tectonism, or climatic variation remains difficult to assess. Primary hydrocarbon reservoirs are developed in well-sorted fine to very fine sandstone units with interparticle porosity that were deposited in middle-shelf positions; secondary reservoirs occur locally in grain-rich carbonate units that are characterized by interparticle or moldic porosity. The Yates and Queen Formations contain the most prolific reservoirs. Younger reservoirs tend to be located basinward of older ones, thus reflecting overall progradation of the Guadalupian reef complex and Guadalupian shelf. Traps are mainly stratigraphic: updip porosity pinch-outs arise from porosity occlusion by anhydrite and top seals are composed of impermeable carbonate and evaporite. Most reservoirs also have structural components, including (1) regional basinward stratal tilt and (2) draping of productive units on deep-rooted anticlines. Systematic thickness variations in many instances reflect structural configurations and indicate that syndepositional tectonic movements persisted through the Late Permian.

Although many common elements of Artesia facies and diagenesis can be abstracted from existing core investigations, additional rock- and well-log-based studies are needed to adequately characterize regional and field-scale facies distributions and controls on reservoir-related porosity and permeability distribution if more effective methods for targeting remaining oil in these reservoirs are to be developed.

The Castile Formation of the Delaware Basin and regionally extensive Salado Formation of the Ochoan Series include thick evaporite deposits and record a long-term salinity crisis in the region. Positioned above the Salado, the Rustler carbonates, evaporites, and siliciclastics mark a relatively abbreviated return of marginal-marine conditions to the region. The Dewey Lake (Midland Basin) and Pierce Canyon Formations (Delaware Basin) mark the youngest episode of preserved Permian deposition in the region, after which a significant net-depositional hiatus prevailed until onset of Late Triassic Lower Dockum Group accumulation. A few sparsely productive, shallow Ochoan reservoirs have been discovered, mainly in the Castile and Rustler. The most important capacity of the Ochoan Series, however, is the dual function of its laterally extensive evaporites as a regional top seal for the underlying Guadalupian reservoir complex and as a guide for hydrocarbon migration from basinal sources into reservoirs situated on the shelves. At present, there appears to be little incentive for exploring potential Ochoan hydrocarbon targets.

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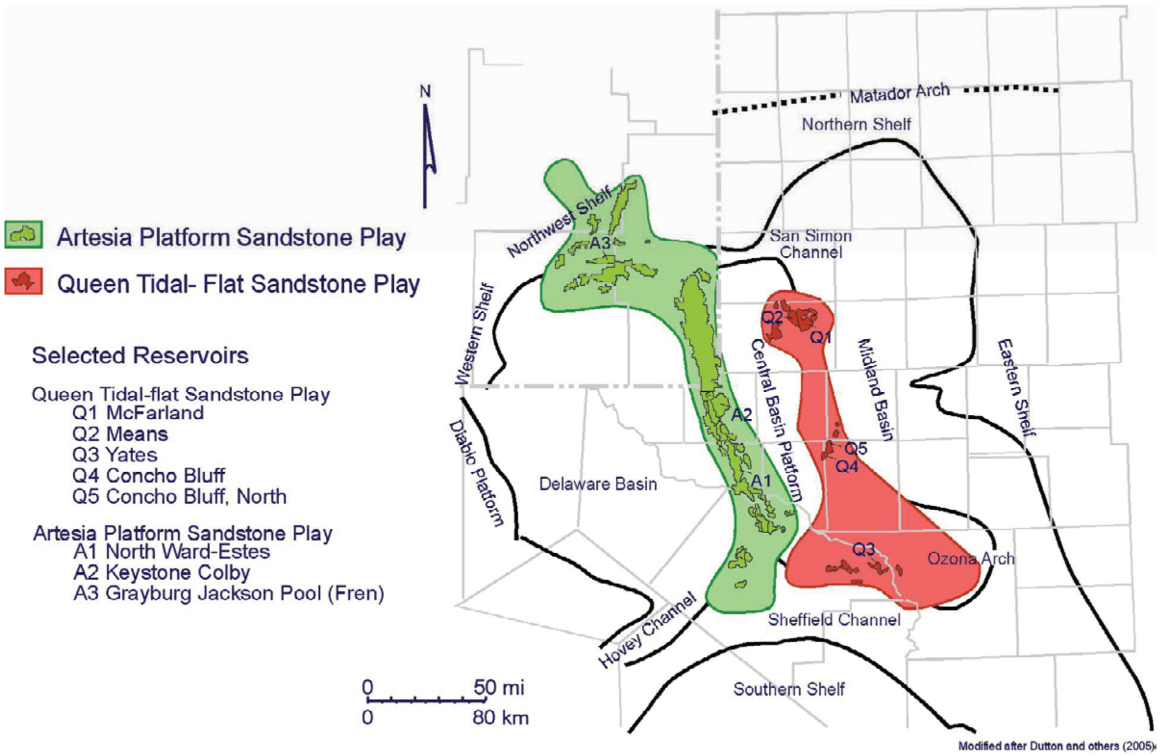

Figure 1. Map showing play boundaries and included oil fields for the Artesia Platform Sandstone Play and the Queen Tidal-Flat Sandstone Play in the Permian Basin. From Dutton and others (2005).

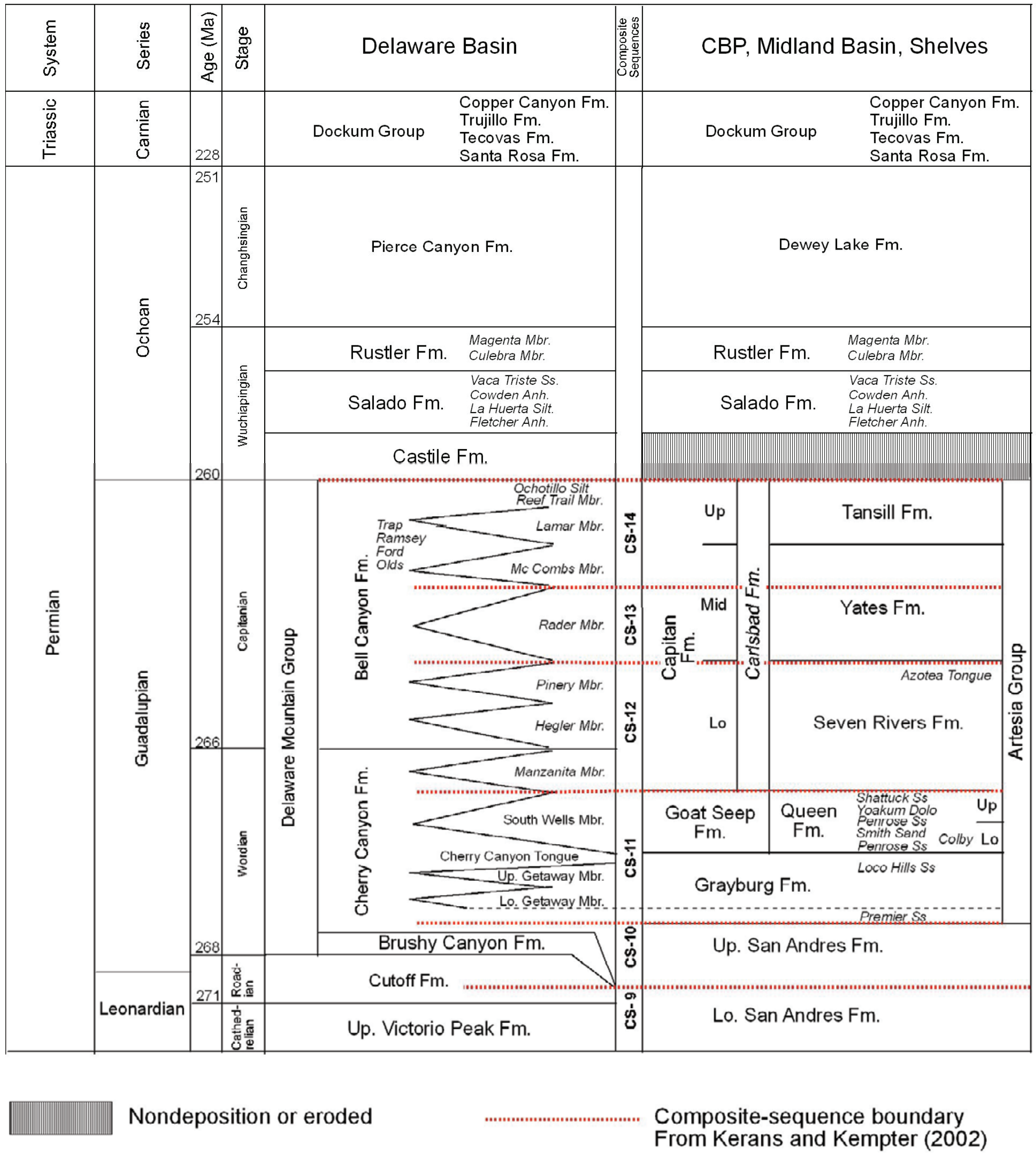

Figure 2. Stratigraphic correlation chart for the Permian Basin. Also shown are composite sequences of Kerans and Kempter (2002). Data from Kerans and Kempter (2002).

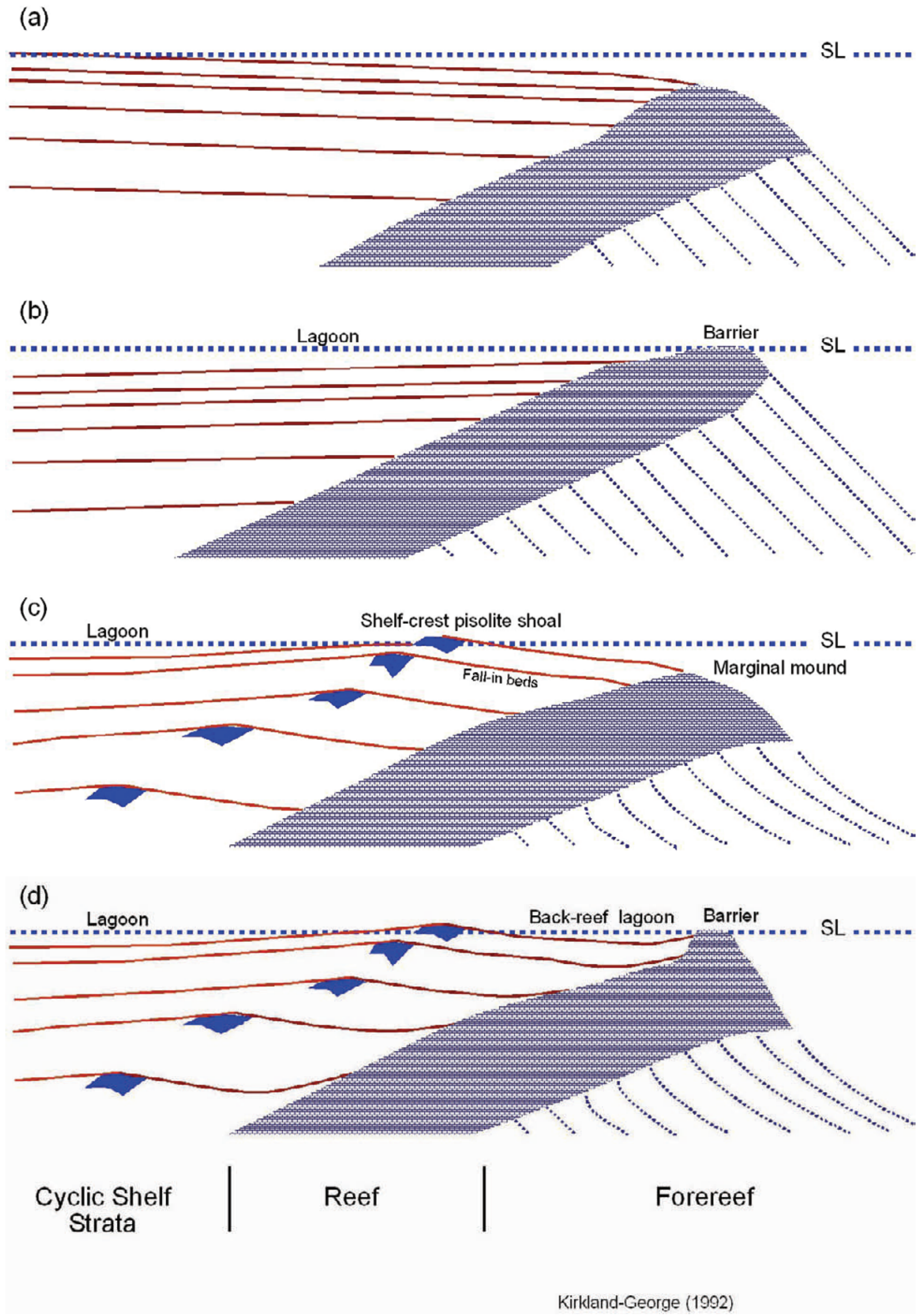

Figure 3. Proposed models for the Guadalupian shelf margin: (a) uninterrupted shelf, (b) barrier reef, (c) marginal mound with pisolite-shoal shelf crest, and (d) barrier island with back-reef lagoon and pisolite shoal. Modified from Kirkland-George (1992).

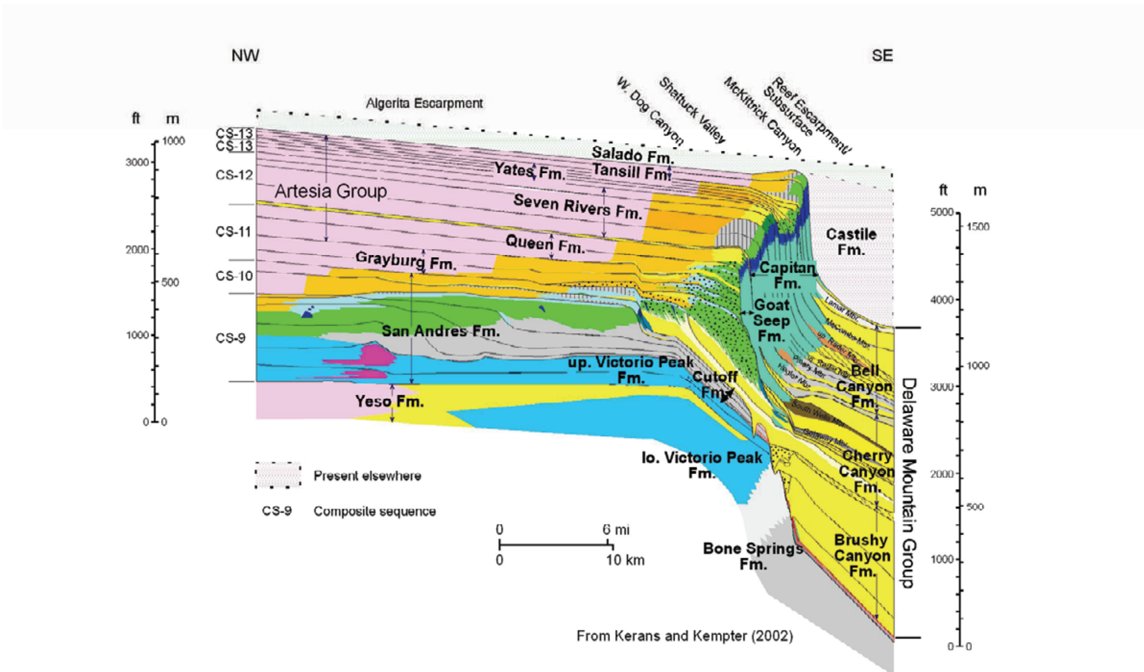

Figure 4. Northwest-southeast schematic cross section of uppermost Leonardian to Ochoan strata, Guadalupe Mountains area, showing formations, carbonate-bearing members of the Delaware Mountain Group, and boundaries of high-frequency sequences and composite sequences. Modified from Kerans and Kempter (2002).

Figure 5. Early Permian paleogeographic global reconstruction of the western hemisphere. Modified from Blakey (2004).

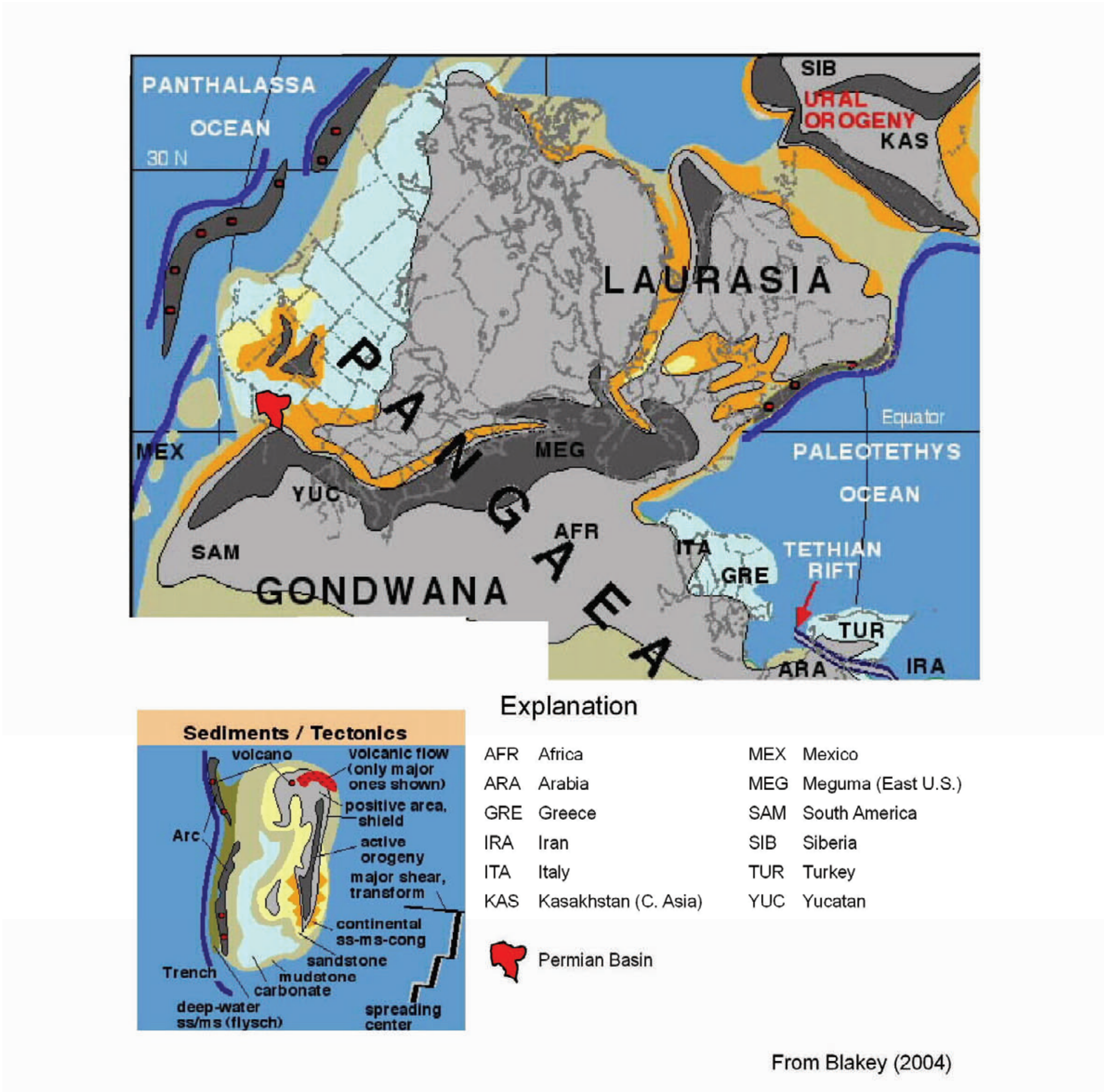

Figure 6. Late Permian paleogeographic reconstruction. Also shown are approximate positions of the Permian Basin. From Blakey (2004).

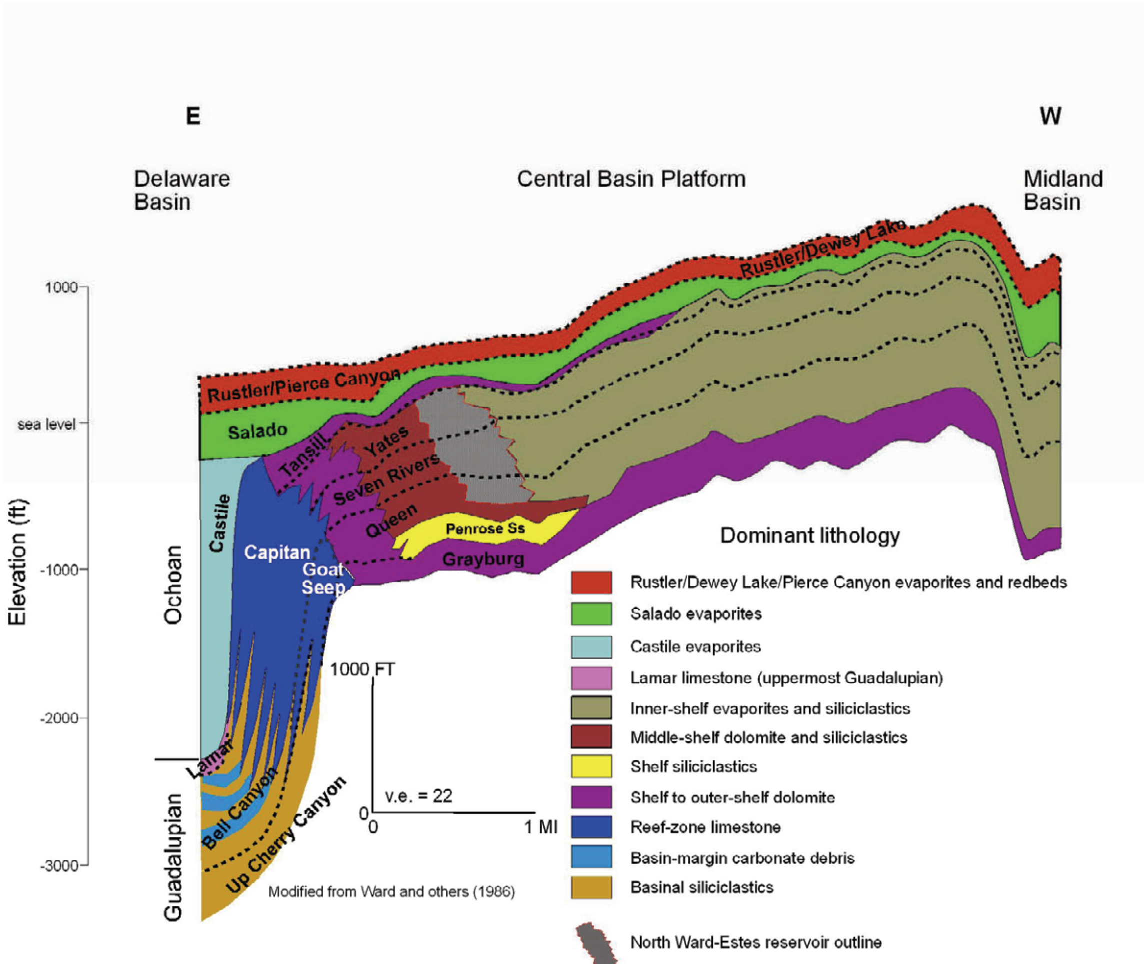

Figure 7. East-west cross section of the Upper Guadalupian shelf intervals and equivalent intervals in the Delaware Mountain Group. Also shown is the North Ward-Estes reservoir. Overall progradational aspect of stratigraphic development is reflected in basinward offsets of stratigraphically younger reservoir units in North Ward-Estes field. Modified from Ward and others (1986).

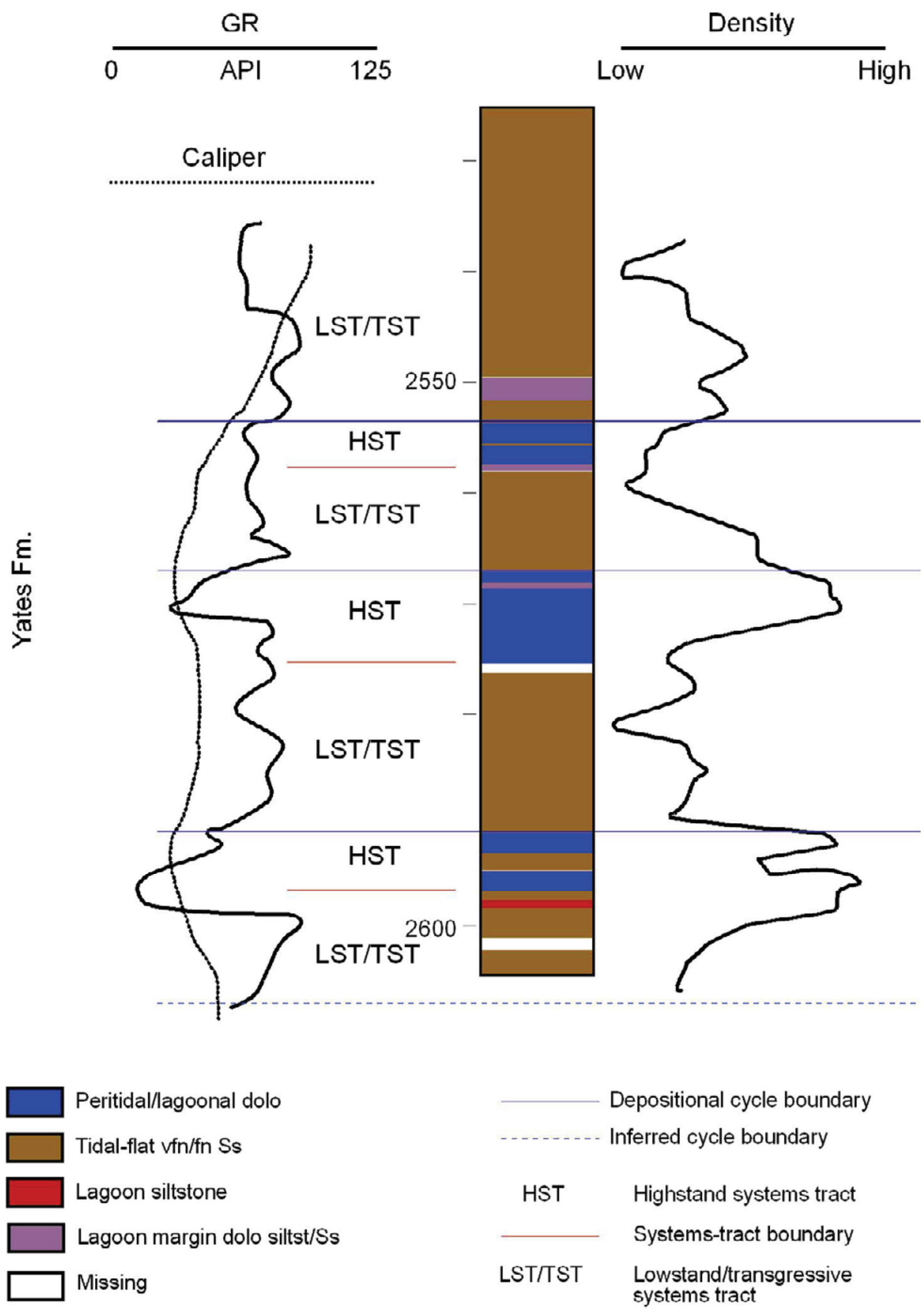

Figure 8. Core description and corresponding well logs for part of the Yates interval from HSA No. 1281, North Ward-Estes reservoir, Ward County. Also shown are boundaries between depositional cycles and systems tracts. Thin siliciclastic breaks in carbonate-dominated intervals may record higher frequency depositional cycles or nearness of carbonate depositional environments to siliciclastic source areas.

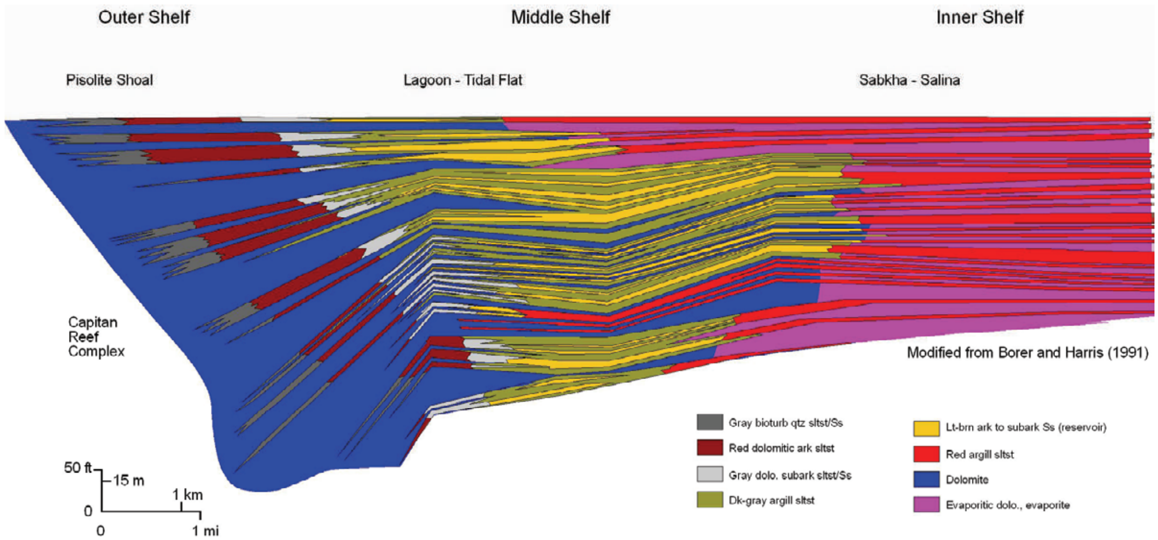

Figure 9. Composite stratigraphic cross section showing shelf-to-basin facies relations in the Yates Formation along the margin of the Delaware Basin. Section was constructed from descriptions of cores from the Northwest Shelf and west edge of the Central Basin Platform. Primary reservoirs are in sandstones of the middle-shelf area. Updip pinch-outs of reservoir sandstones into evaporate-bearing siliciclastics and stratigraphically adjacent evaporate-bearing and evaporate strata (top and bottom seals) compose the stratigraphic components of hydrocarbon trapping. Modified from Borer and Harris (1991).

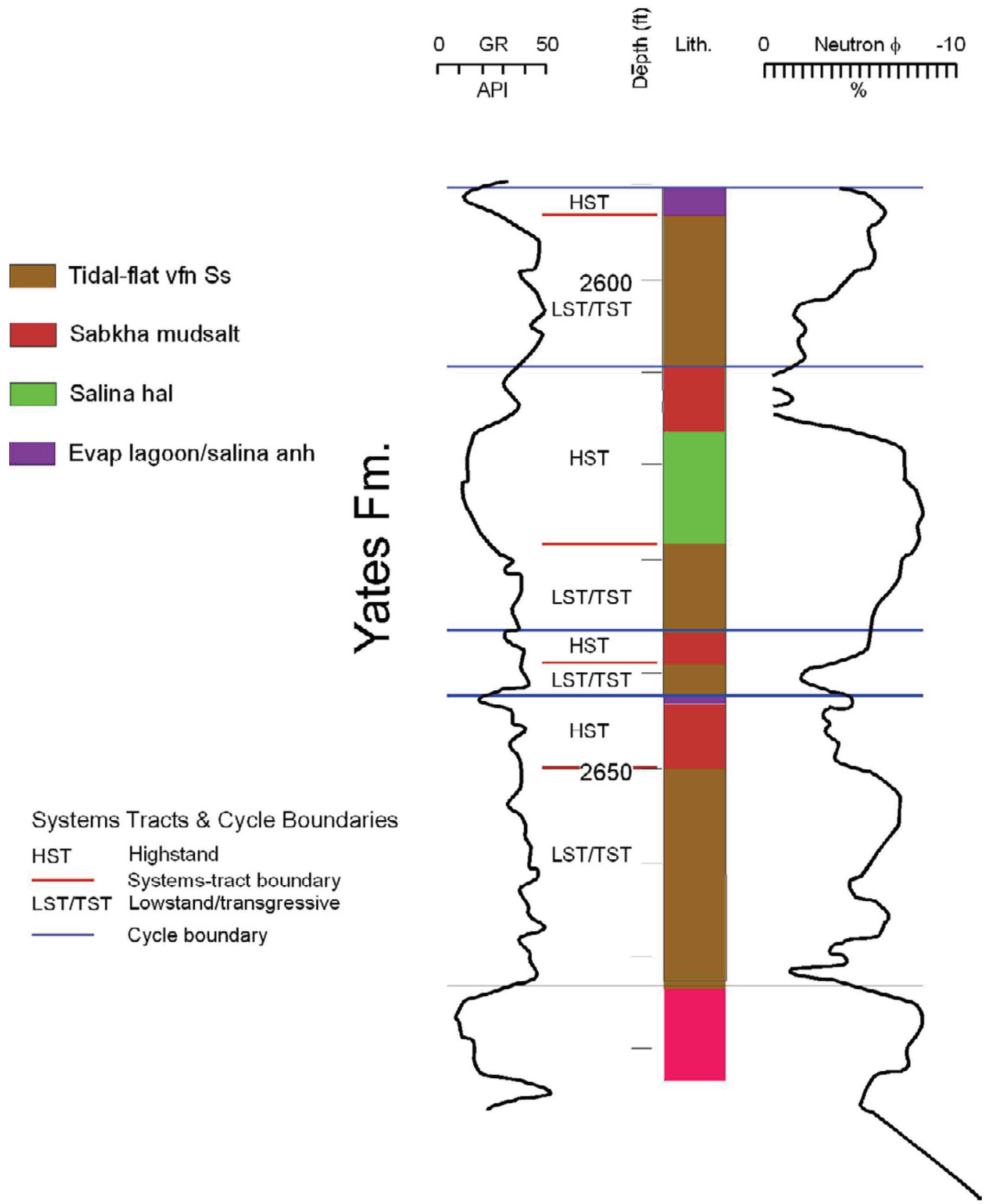

Figure 10. Core description and corresponding well logs for a part of the Yates interval from University No. 3210-2, Embar reservoir, Andrews County. Also shown are boundaries between depositional cycles and systems tracts. The evaporite facies in this well are representative of areas that are up depositional dip of those represented by carbonate facies, such as are shown in HSA No. 1281 well (fig. 8).

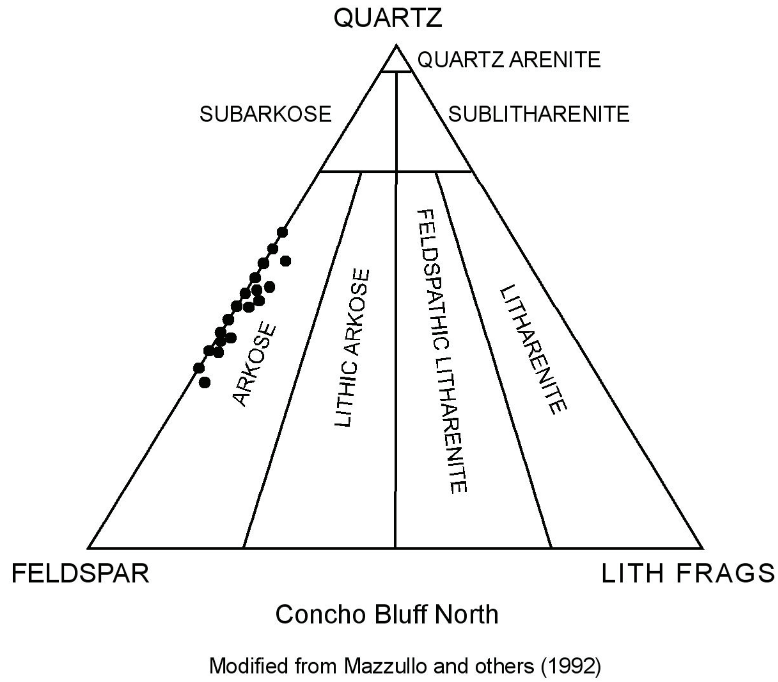

Figure 11. Ternary composition diagram for North Concho Bluff sandstone (classification of Folk, 1968). Diagram is generally representative of Guadalupian sandstone and siltstone compositions in the Permian Basin. The significant fraction of K-feldspar produces relatively high gamma-ray values even in clay-free sandstone. Modified from Mazzullo and others (1992).

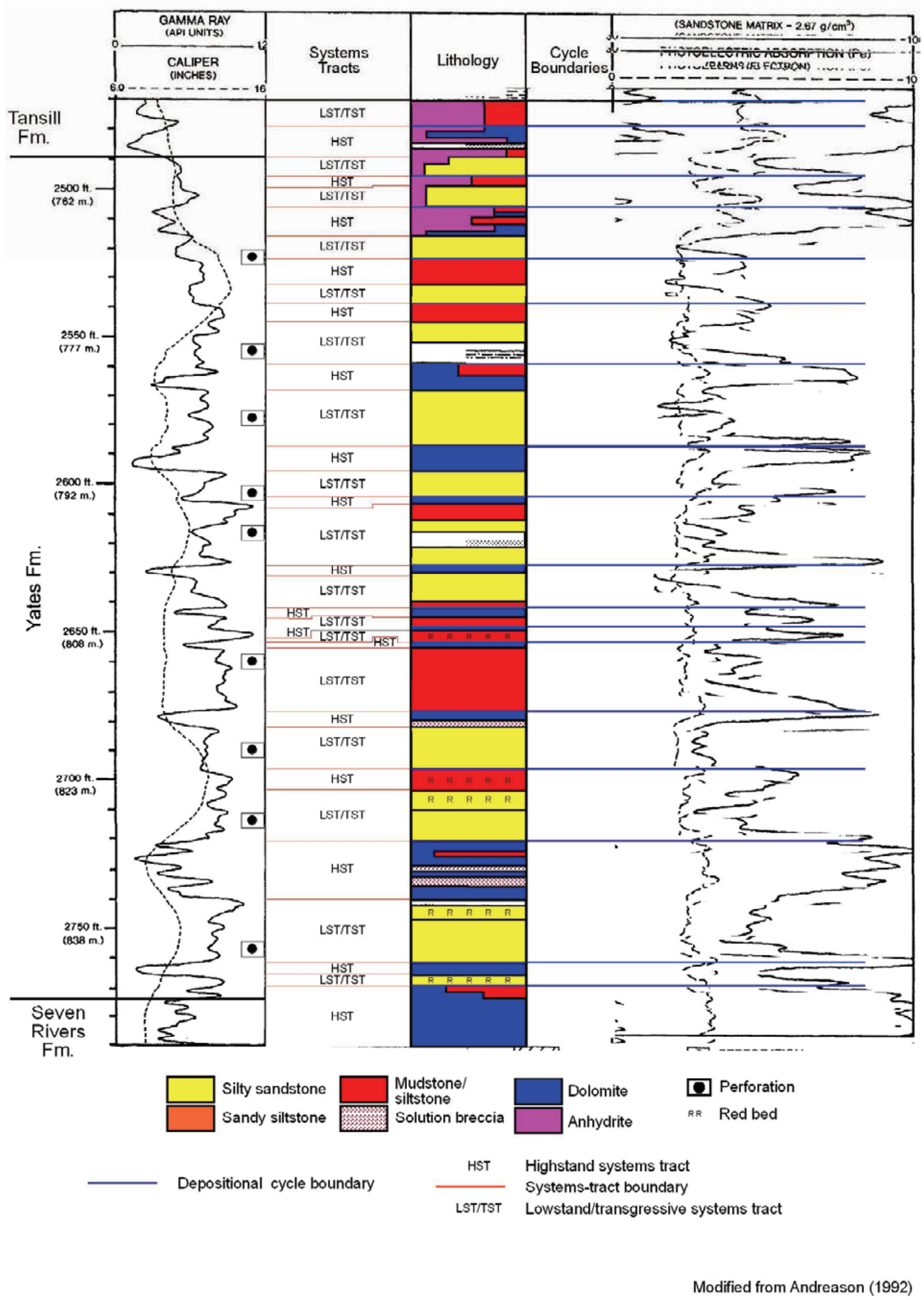

Figure 12. Core description and corresponding well logs of the Yates interval from HSA No. 1281, North Ward-Estes reservoir, Ward County. Also shown are boundaries between depositional cycles and systems tracts. Note that evaporites (anhydrite) are more common in the uppermost parts of the Yates, reflecting the overall reduction of accommodation during deposition of marine-derived chemical portions of the formation. Note also the thinning of carbonate units at higher stratigraphic intervals in the lower half of the Yates. The return of thicker carbonate beds above the 2,600-ft level may mark the mid-Yates sea-level turnaround interpreted by Kerans and Kempter (2002) in the Guadalupe Mountains (CS13/CS14 boundary in figure 2). Modified from Andreason (1992).

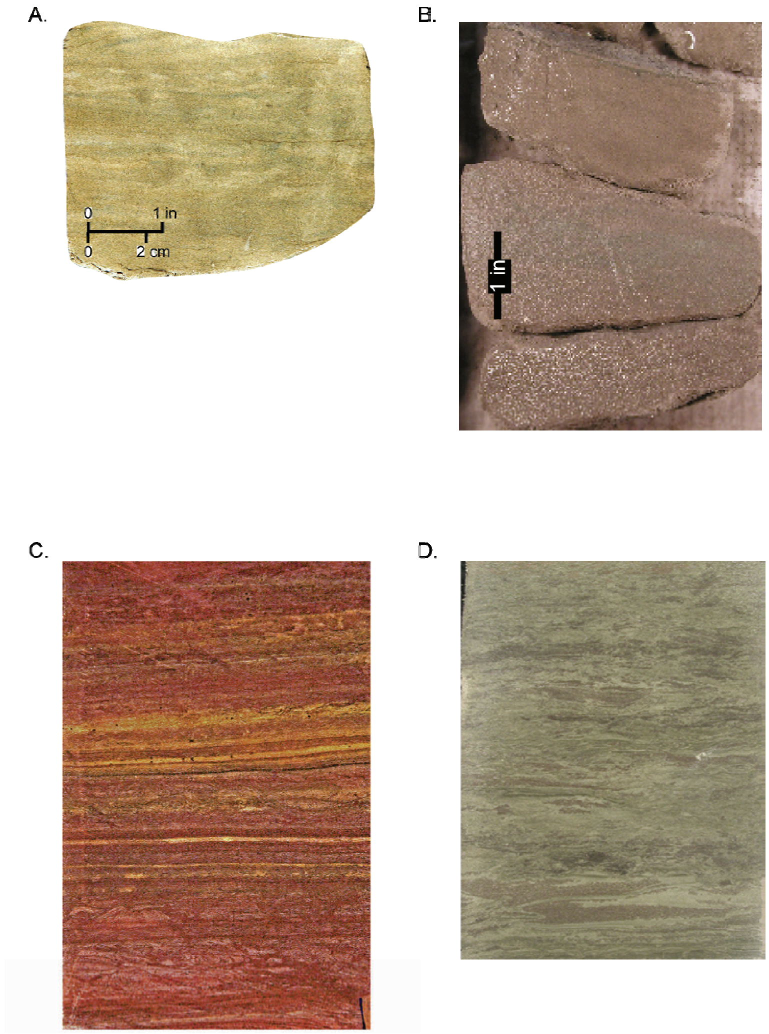

Figure 13. Artesia Group beach-ridge and tidal-flat sandstone facies: (A) Queen reservoir (oil-stained) beach-ridge, coarsely laminated, fine-grained feldspathic sandstone (HSA No. 475 well, North Ward-Estes, Ward County); (B) Yates reservoir (oil-stained) beach-ridge, coarsely laminated, fine-grained feldspathic sandstone (HSA No. 1257 well, North Ward-Estes, Ward County); (C) Queen nonreservoir, mm-scale, planar- and ripple-laminated, fine/very fine grained sandstone (HSA No. 475 well, North Ward-Estes, Ward County);and (D) Yates haloturbated, mm-scale, planar- and ripple-laminated, fine/very fine grained sandstone (HSA No. 1281 well, North Ward-Estes, Ward County).

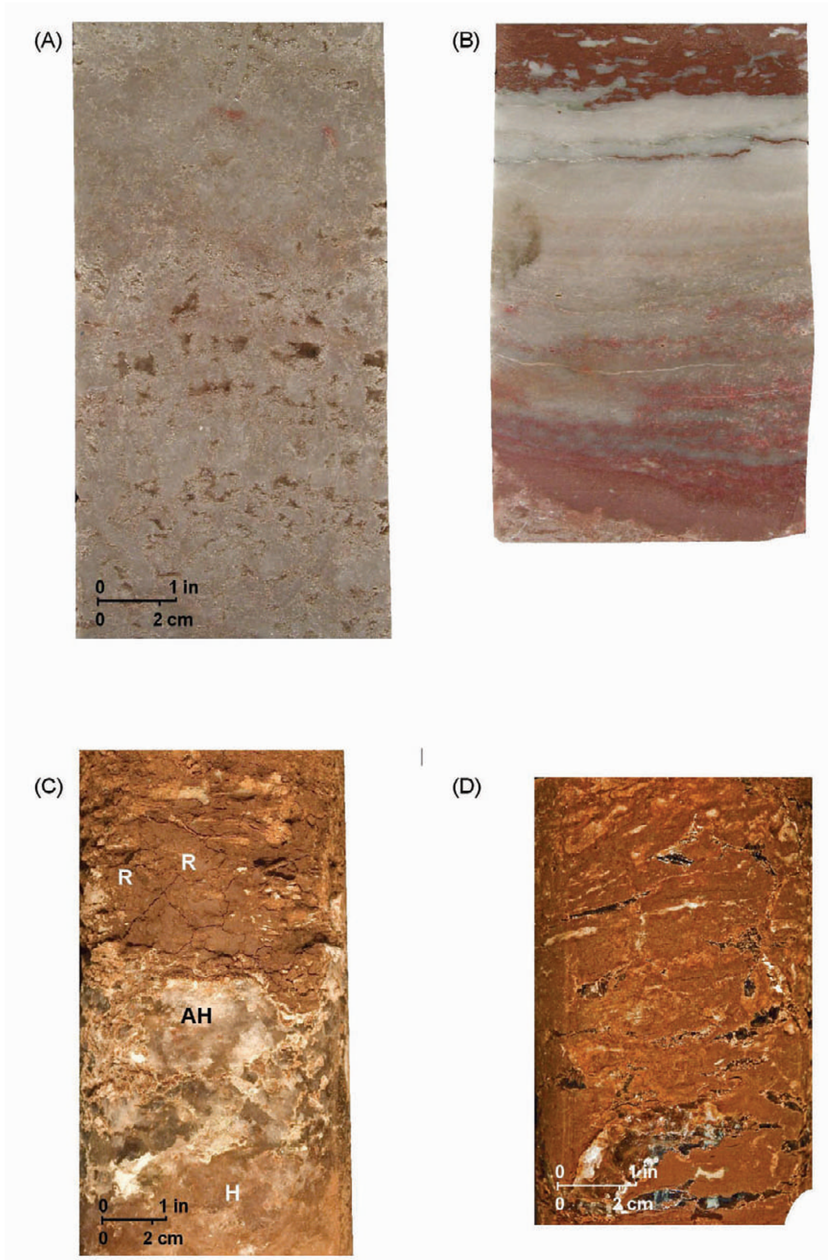

Figure 14. Artesia Group evaporite facies (University No. 3210-2 well, Embar field, Andrews County): (A) Yates Formation brine-pool, vuggy to massive, nodular anhydrite; vugs are filled with halite and may be molds after gypsum crystals; alternatively, vuggy interval may be fenestral tidal-flat carbonate that has been replaced by sulfate; (B) Yates brine-pool, plane-laminated anhydrite may record cycles of gypsum growth and abrasion in a shallow pool; (C) brine-pool and brine-pool-margin (sabkha) succession of mosaic halite, anhydritic halite, and mudrock residue after dissolution of halite from mixed halite-mudrock facies; and (D) sabkha, silty, very fine grained sandstone containing cm-scale halite crystals. Dissolution of halite would produce haloturbated sandstone such as is shown in figure 13D.

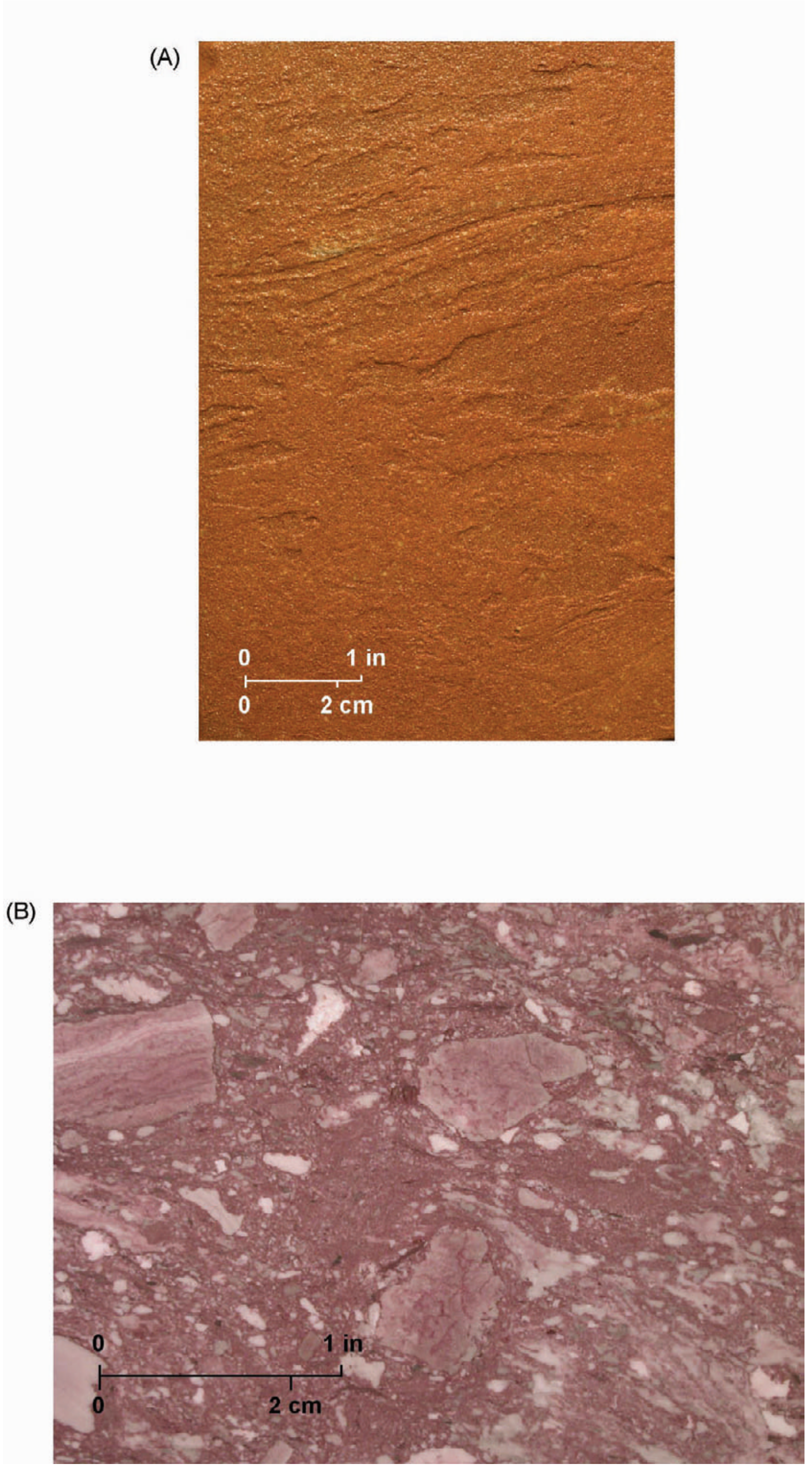

Figure 15. Artesia Group eolian sandstone and mixed sandstone/carbonate facies: (A) Yates uncommon, ripple-laminated, fine-grained sandstone from probable eolian setting (University No. 3210-2 well, Embar field, Andrews County) and (B) Yates dissolution-collapse-brecciated dolomite in siliciclastic matrix. Facies is similar to that found in dissolution zone depicted in figure 31 (HSA No. 1281 well, North Ward-Estes, Ward County).

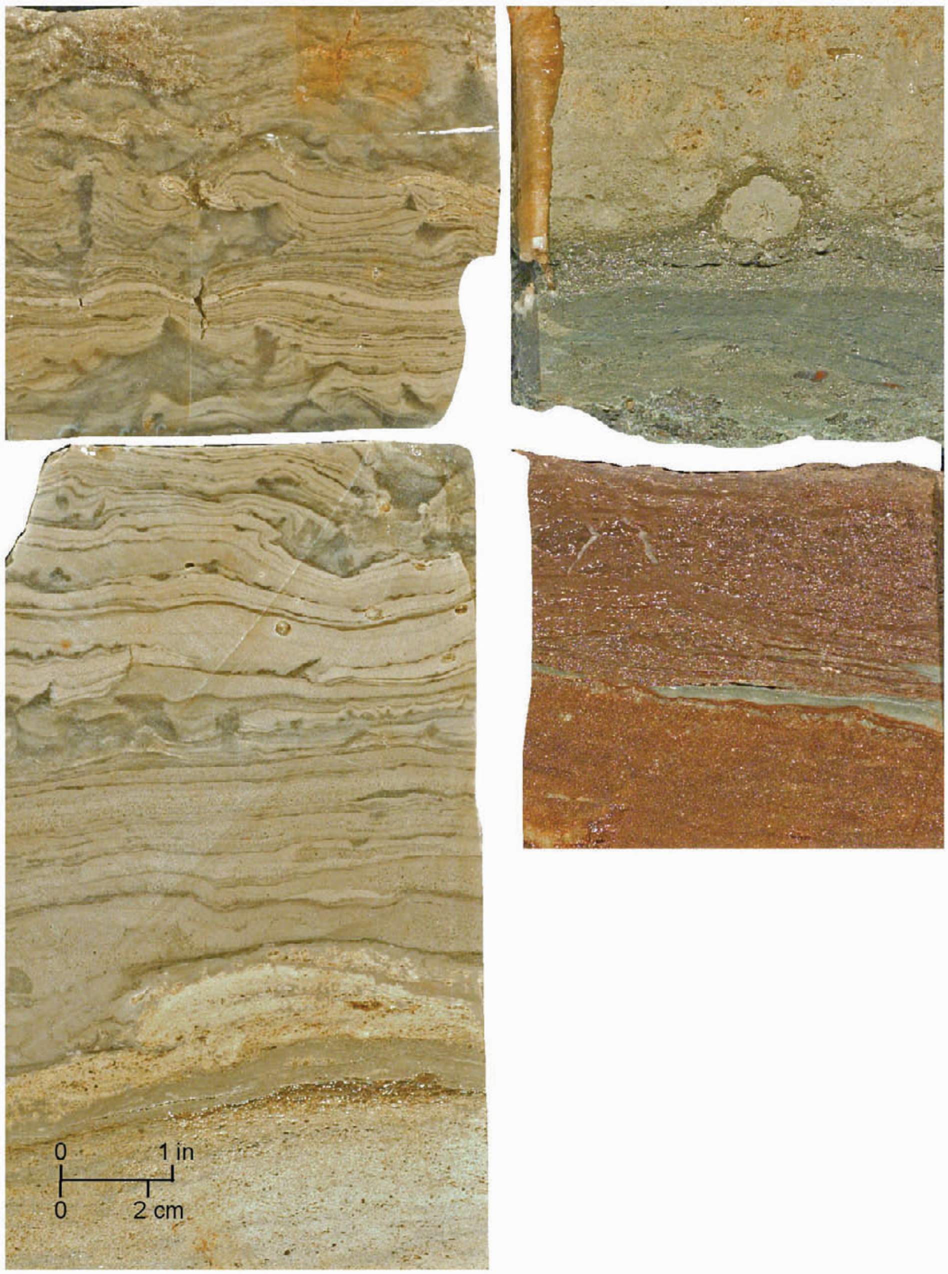

Figure 16. Yates succession of tidal-flat, haloturbated, fine- to very fine grained sandstone and anhydritic dolomite; it may record transgressive reworking of terrestrial sandstone into tidal flats and establishment of evaporative lagoon wherein algal-laminated carbonate deposition alternates with gypsum precipitation. Upper half of carbonate-anhydrite interval shows carbonate draping over pseudomorphs after standing gypsum crystals (University No. 3210-2 well, Embar field, Andrews County).

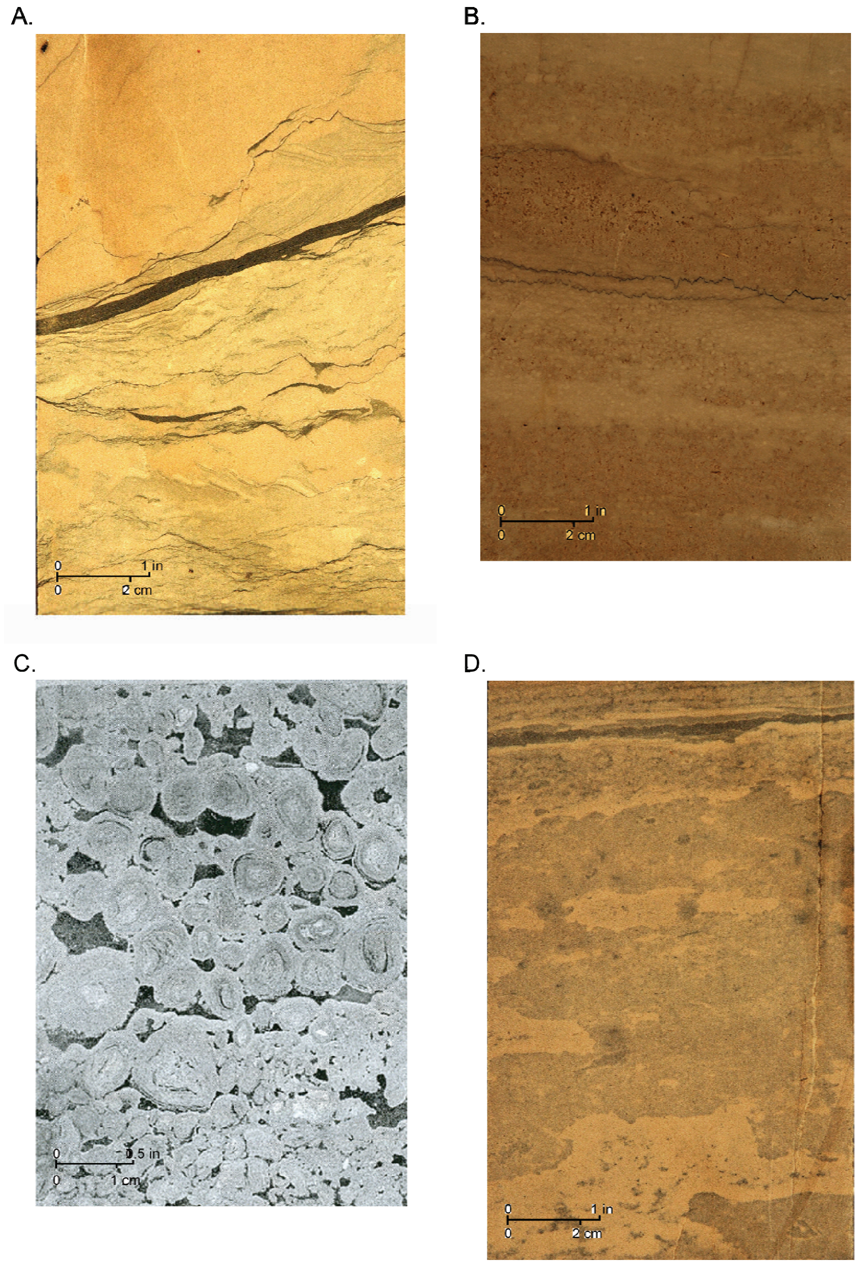

Figure 17. Artesia Group dolostone facies: (A) Queen shoal cross-laminated grainstone; (B) Queen tidal-flat packstone; (C) Yates shelf-crest shoal, pisolite grainstone; and (D) Queen lagoon bioturbated wackestone to packstone. Cores A, B, and D are from HSA No. 475 well, Ward-Estes, Ward County; C is from Gulf PDB-04 well, Eddy County, New Mexico.

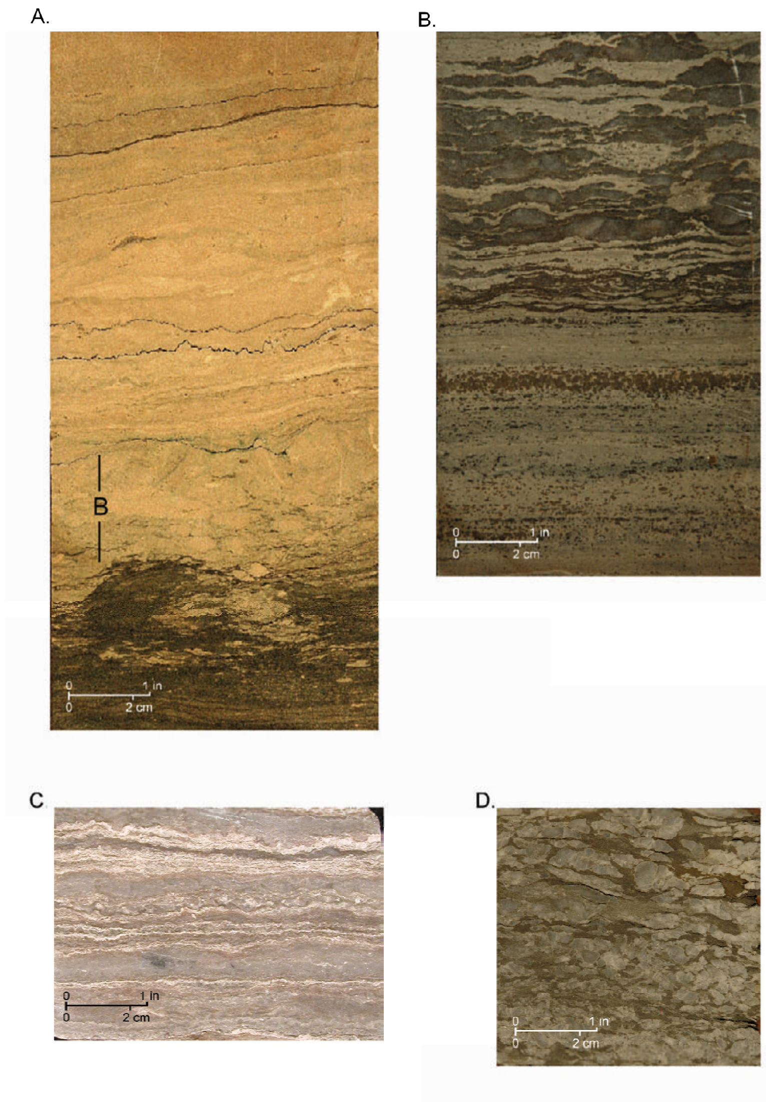

Figure 18. Artesia dolostone and evaporite facies: (A) succession of Queen tidal-flat, laminated siliciclastic siltstone; collapse-breccia dolostone; and tidal-flat, algal-laminated wackestone/packstone (HSA No. 475 well, Ward-Estes, Ward County);
(B) succession of tidal-flat dolostone with mm-scale anhydrite (sabkha) and interlaminated brine-pool dolomudstone and anhydrite (HSA No. 475 well, Ward-Estes, Ward County); succession records establishment of a sabkha in a previously deposited tidal-flat interval and subsequent development of a brine pool wherein conditions alternated between sulfate undersaturation (carbonate laminae) and supersaturation (anhydrite intervals); (C) Yates brine-pool, mm-scale, interlaminated dolomite (thin laminae) and anhydrite (University No. 3210-2 well, Embar field, Andrews County); and (D) Seven Rivers sabkha anhydrite in siliciclastic matrix (HSA No. 475 well, Ward-Estes, Ward County).

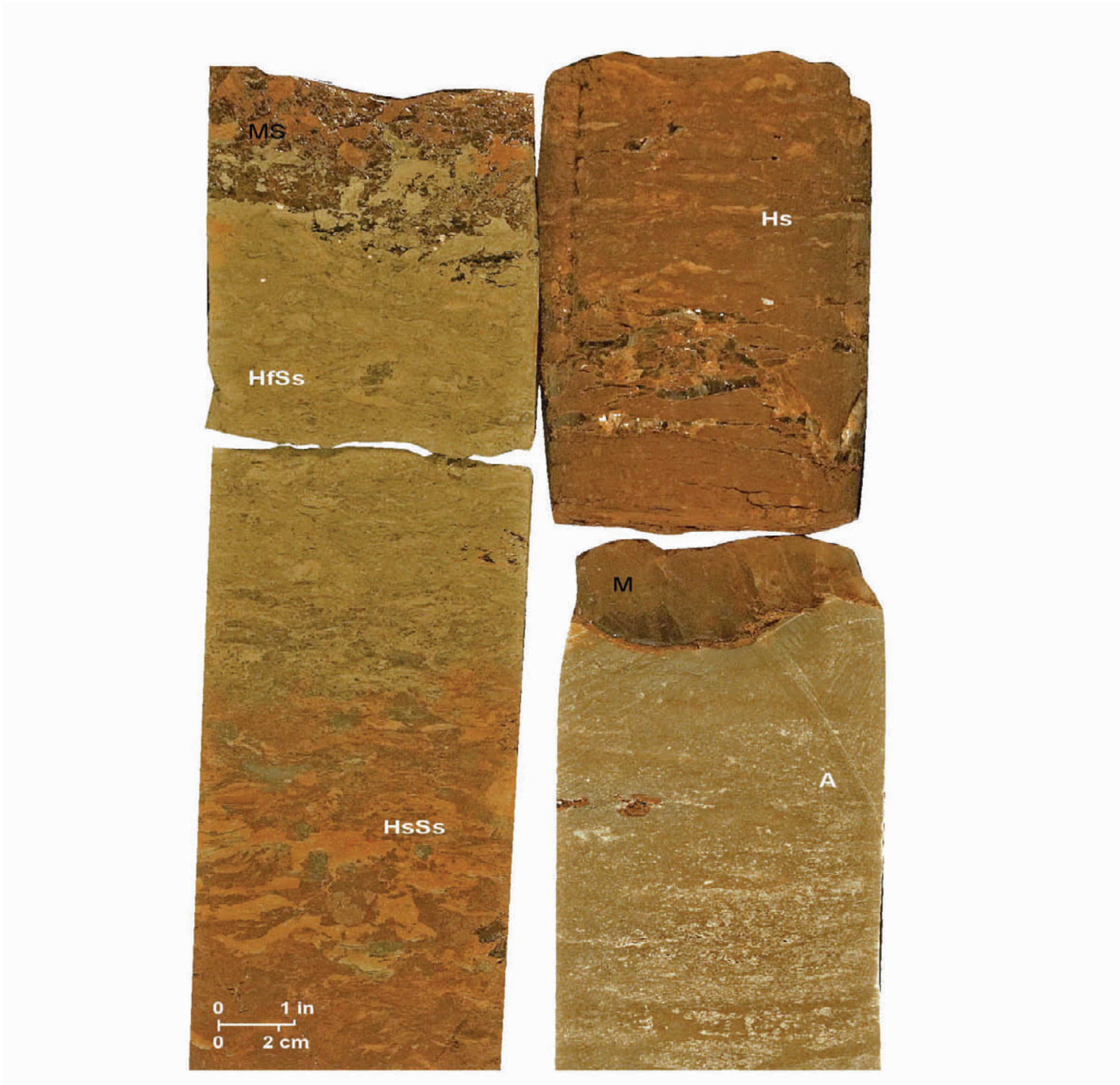

Figure 19. Succession of Yates brine-pool anhydrite, brine-pool fill of mudrock and haloturbated siltstone to fine-grained sandstone, and sabkha halite-mudrock (University No. 3210-2 well, Embar field, Andrews County). A = brine-pool anhydrite; M = brine-pool-margin mudstone residue after halite dissolution in halite-mudrock; Hs = sabkha haloturbated, sandy siltstone; HsSs = sabkha haloturbated, silty, very fine grained sandstone; HfSs = sabkha haloturbated, fine-grained sandstone; and MS = sabkha admix of halite and fine-grained sandstone. MS is representative of HfSs prior to halite dissolution. Prior to halite dissolution mosaic halite may have occurred immediately above the anhydrite.

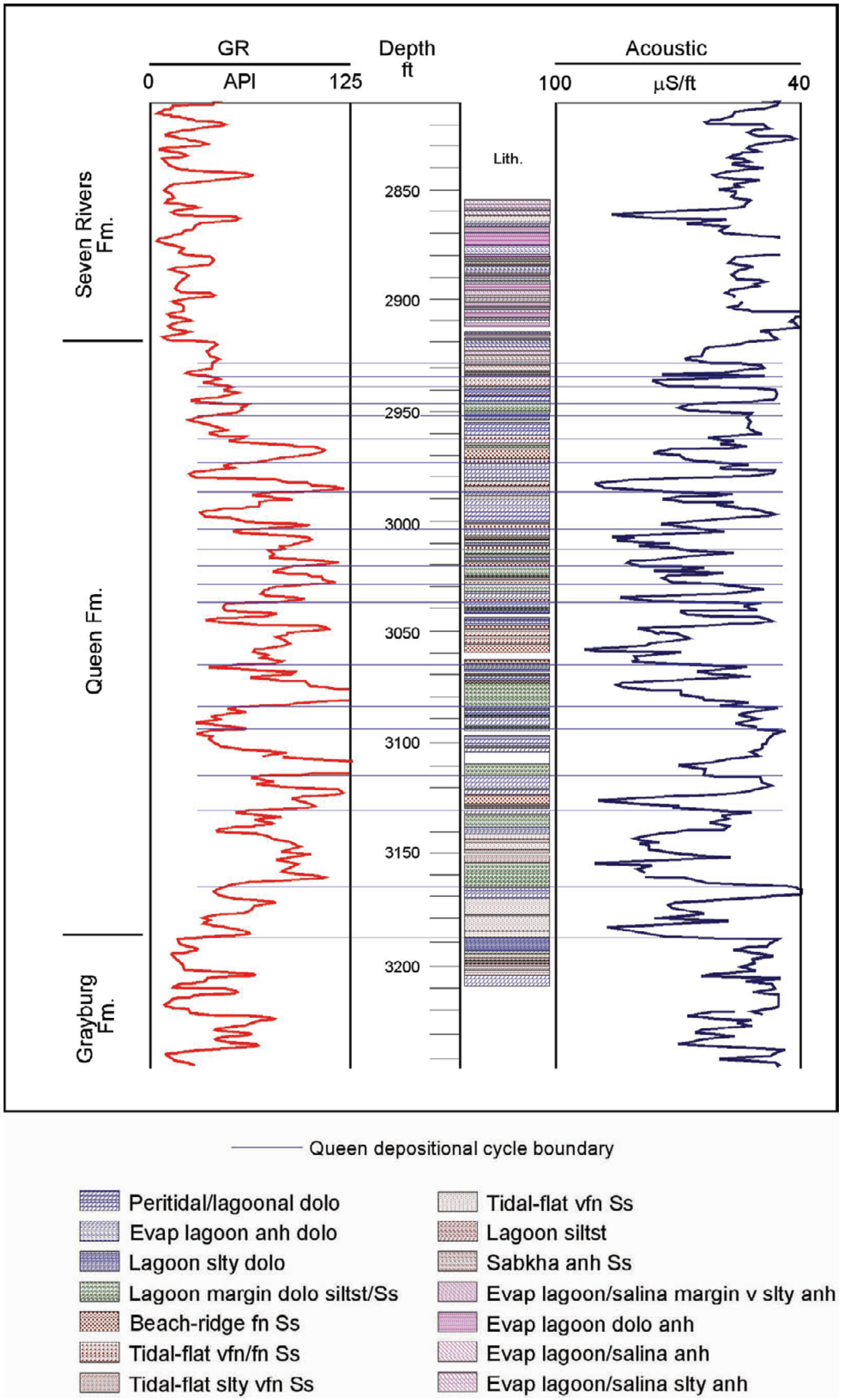

Figure 20. Core description and well logs for Queen Formation and stratigraphically adjacent units from HSA No. 475, N. Ward-Estes reservoir, Ward County. Also shown are depositional cycle boundaries within the Queen.

Figure 21. Queen peritidal dolopackstone with tepee structure and probable replacive anhydrite. Swirl in lower part of upper anhydrite interval is composed of dolomite inclusions.

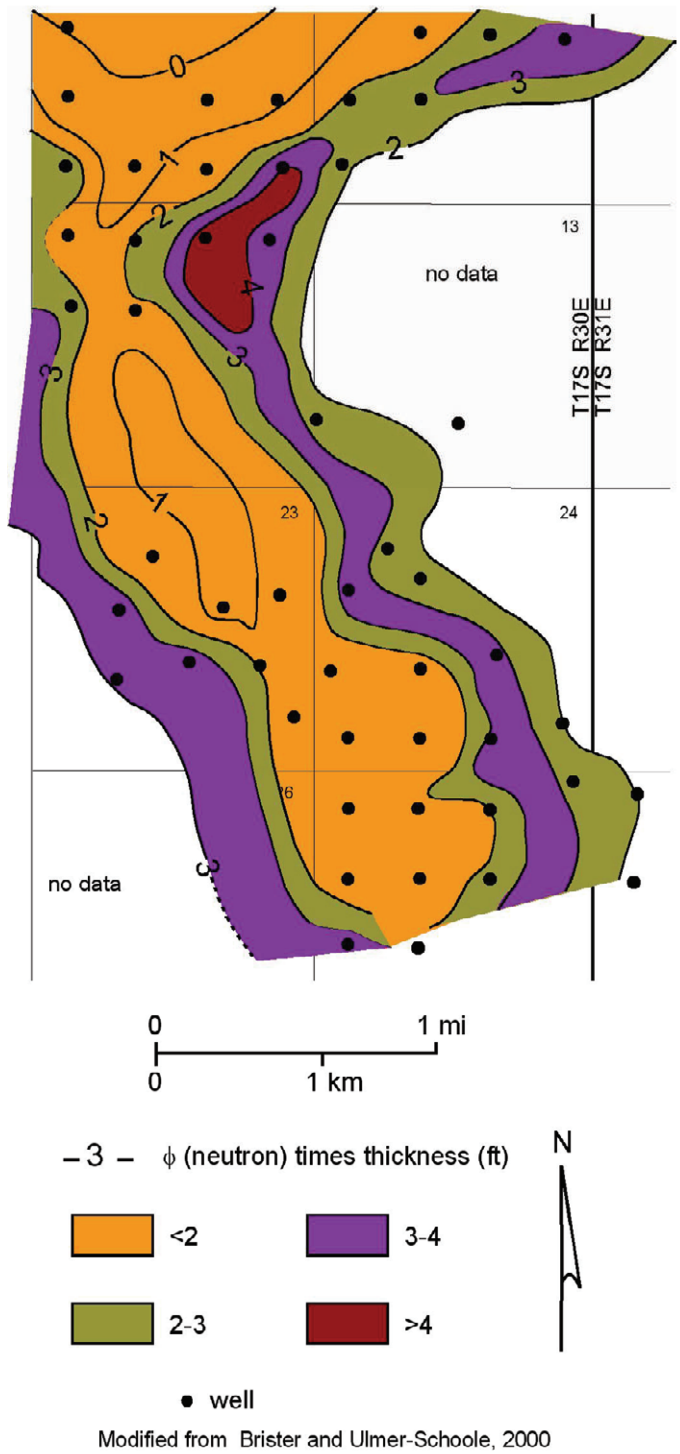

Figure 22. Neutron-porosity-thickness map of Seven Rivers dolograinstone interval, Grayburg-Jackson (formerly Fren) pool, Eddy County. Feature is interpreted to record a tidal-channel deposit. Modified from Brister and Ulmer-Scholle, 2000.

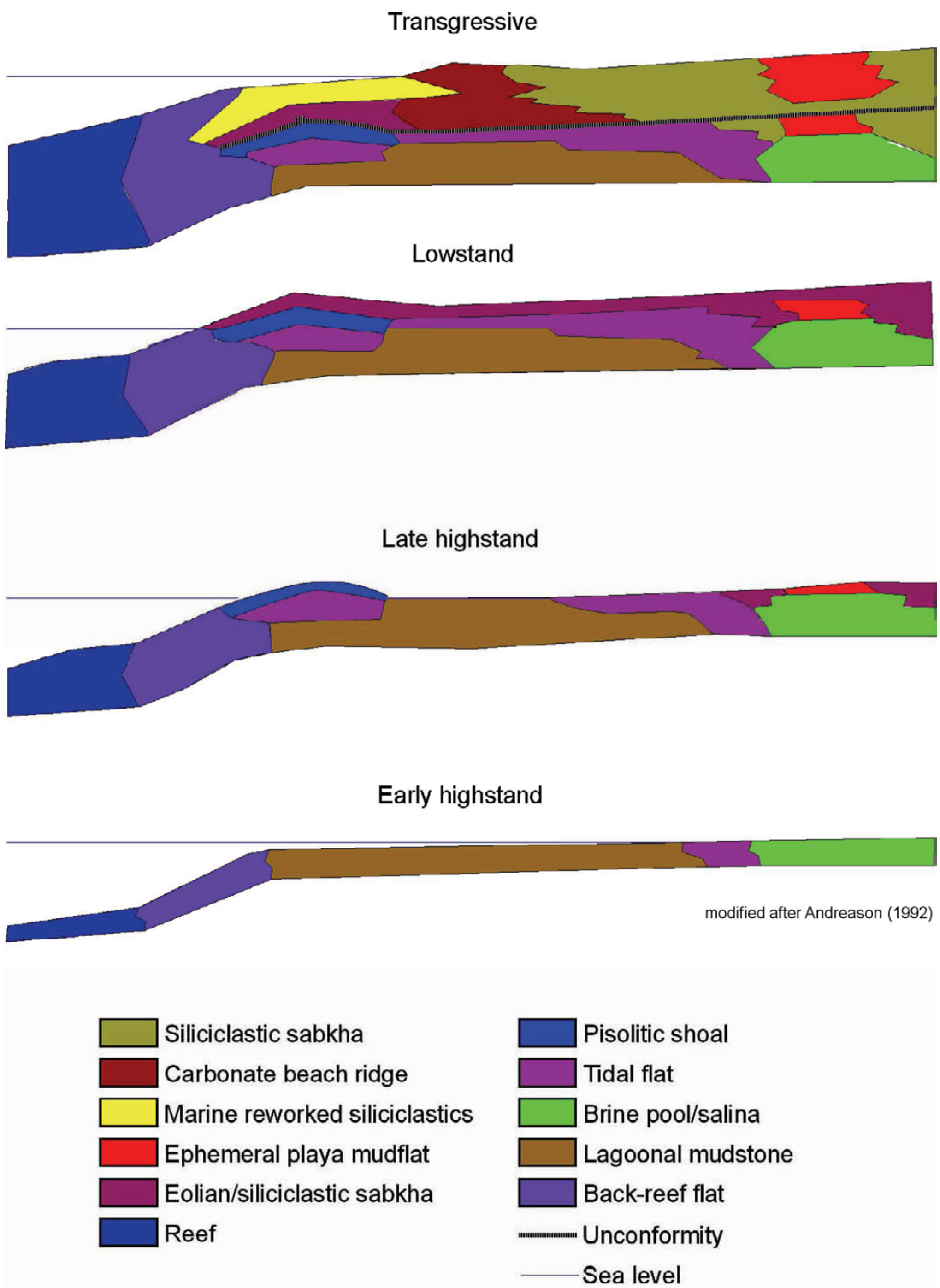

Figure 23. Shelf-margin to inner-shelf cross sections schematically illustrating sea-level-related stages of Yates deposition at Ward-Estes field. Model is generally representative of Upper Permian depositional styles. Modified from Andreason (1992).

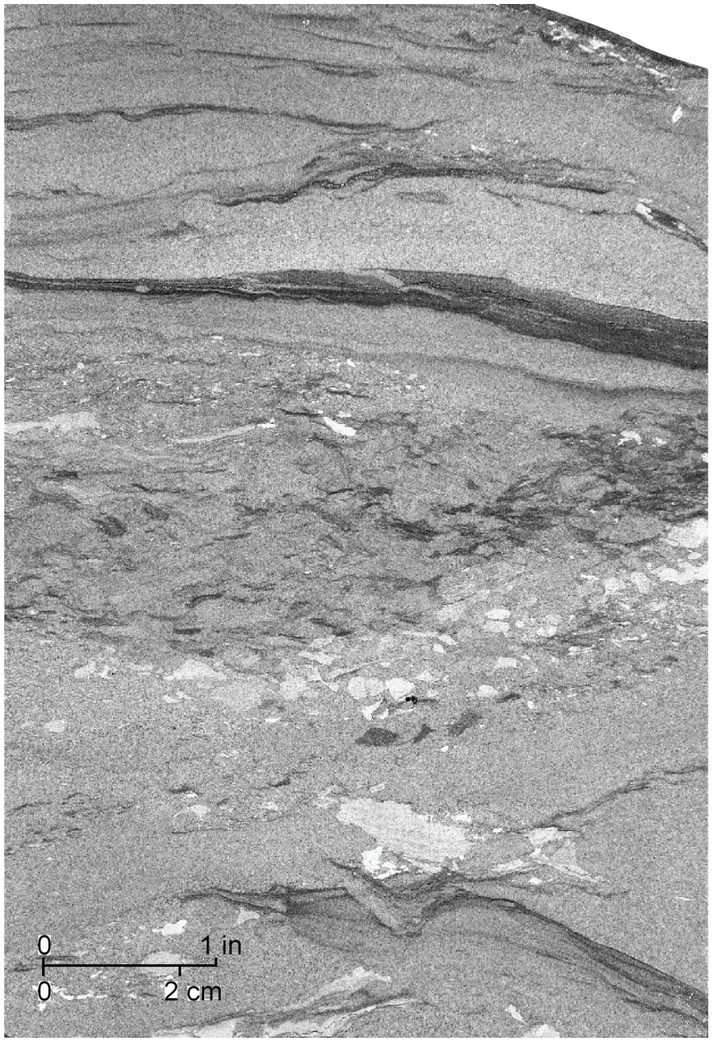

Figure 24. Queen intraclastic, fine-grained sandstone of possible tidal-channel origin. This sample lies below a marine-derived cycle-top dolostone bed and may record a transgressive ravinement surface. Similar samples elsewhere may mark high-frequency sequence boundaries within siliciclastic intervals where no marine-derived sediment was deposited during the highstand depositional phase (HSA No. 475 well, 2945.5 ft, North Ward-Estes reservoir, Ward County).

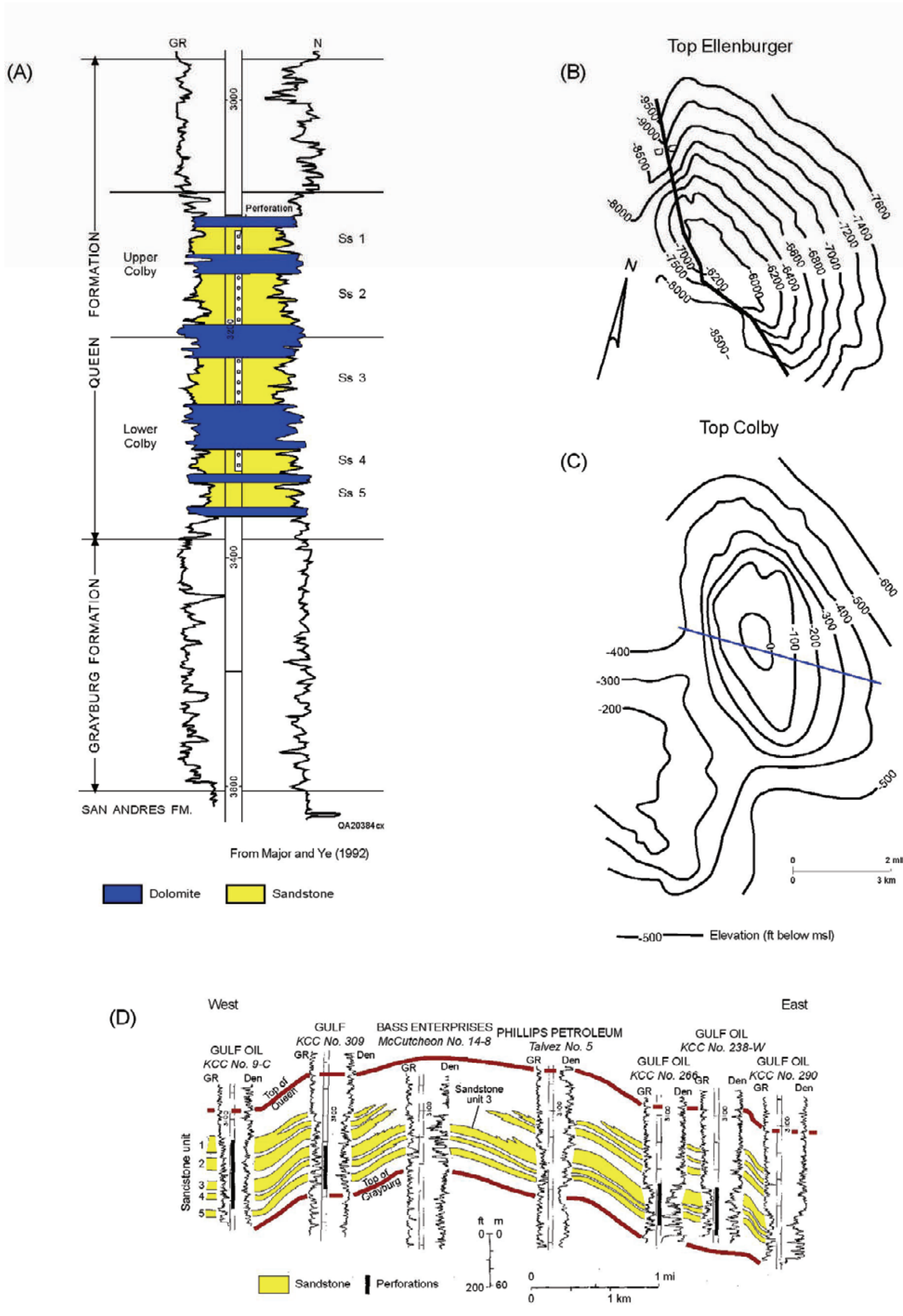

Figure 25. Keystone Colby reservoir: (A) representative well log showing reservoir sandstone intervals and stratigraphically adjacent dolostone intervals; structure maps on the tops of the (B) Ellenberger Formation and (C) Colby (Queen) sandstone interval, demonstrating the deeply rooted origins of structures in the Upper Permian section; and (D) west-east cross section of the Colby sandstone interval showing off-structure thickening of the Queen and reservoir-sandstone pinch-outs onto the Keystone structure. Approximate line of section shown in C. Modified from Galloway and others (1983) and Major and Ye (1997).

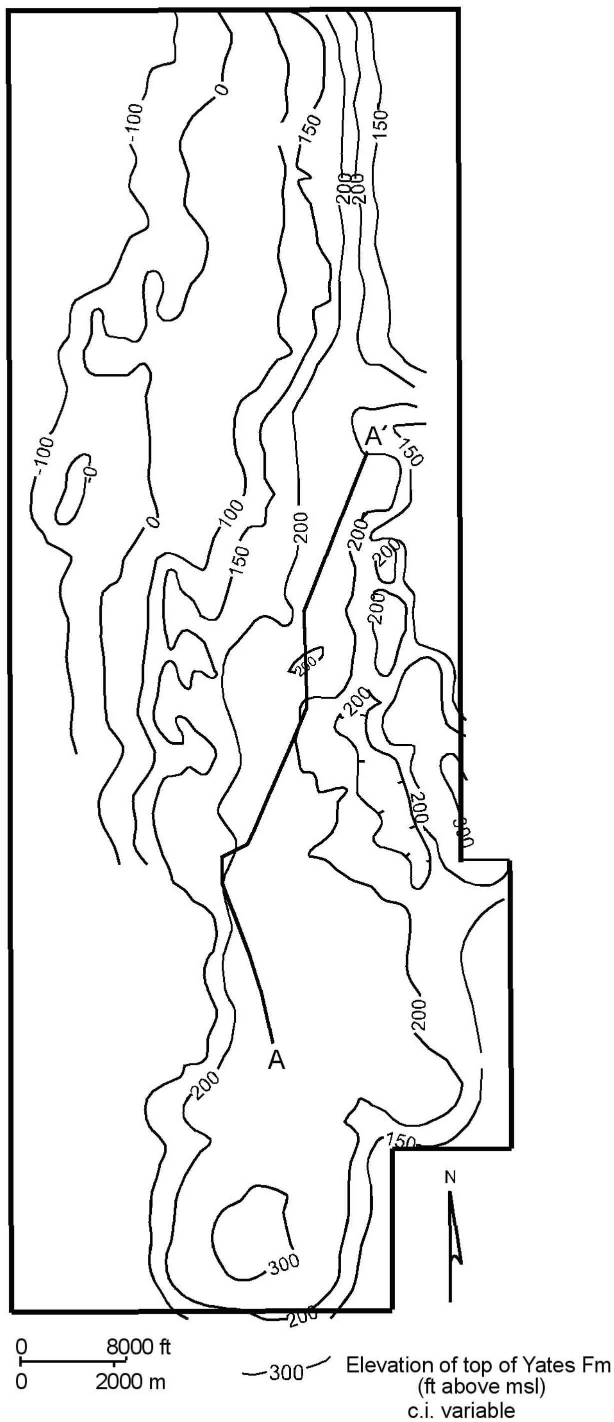

Figure 26. Structure map on top of the Yates Formation, North Ward-Estes reservoir, Ward County. Location of section A-A′ (figure 32) is shown. Primary structure is a narrow strike-elongate anticline. Modified from West Texas Geological Society (1994).

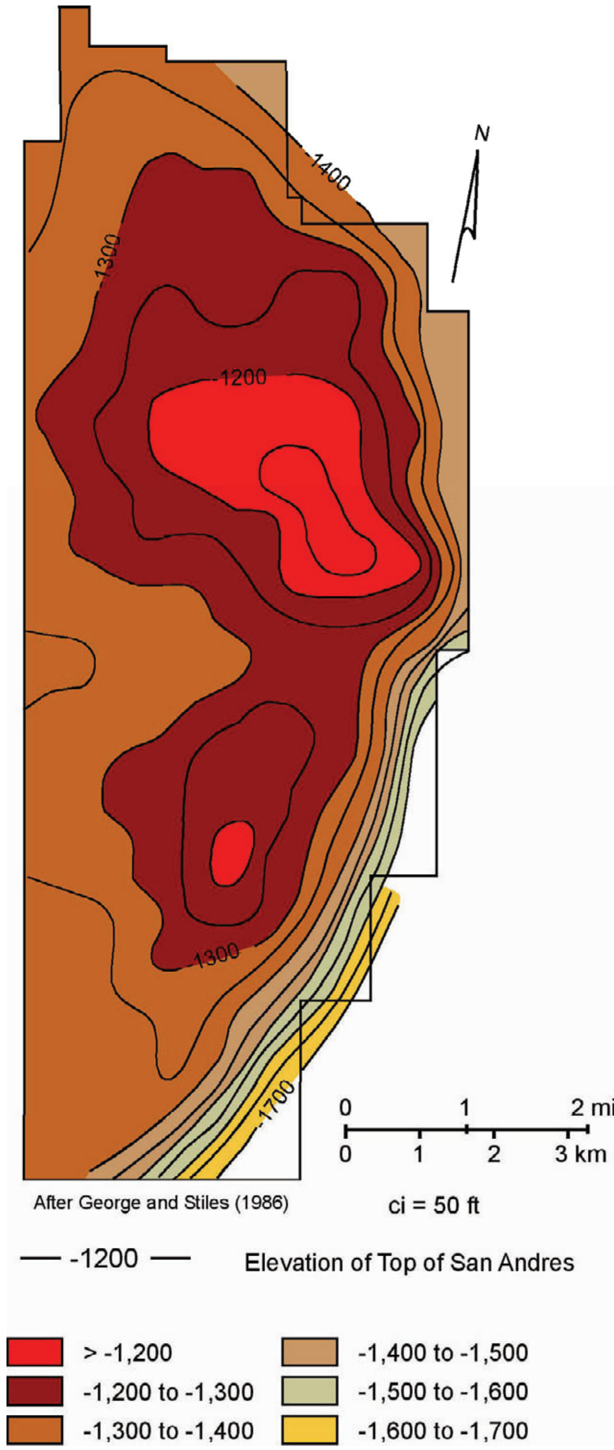

Figure 27. Structure map on top of the Queen Formation, Means reservoir, Andrews County, showing twin-domal configuration reservoir structure. After George and Stiles (1986).

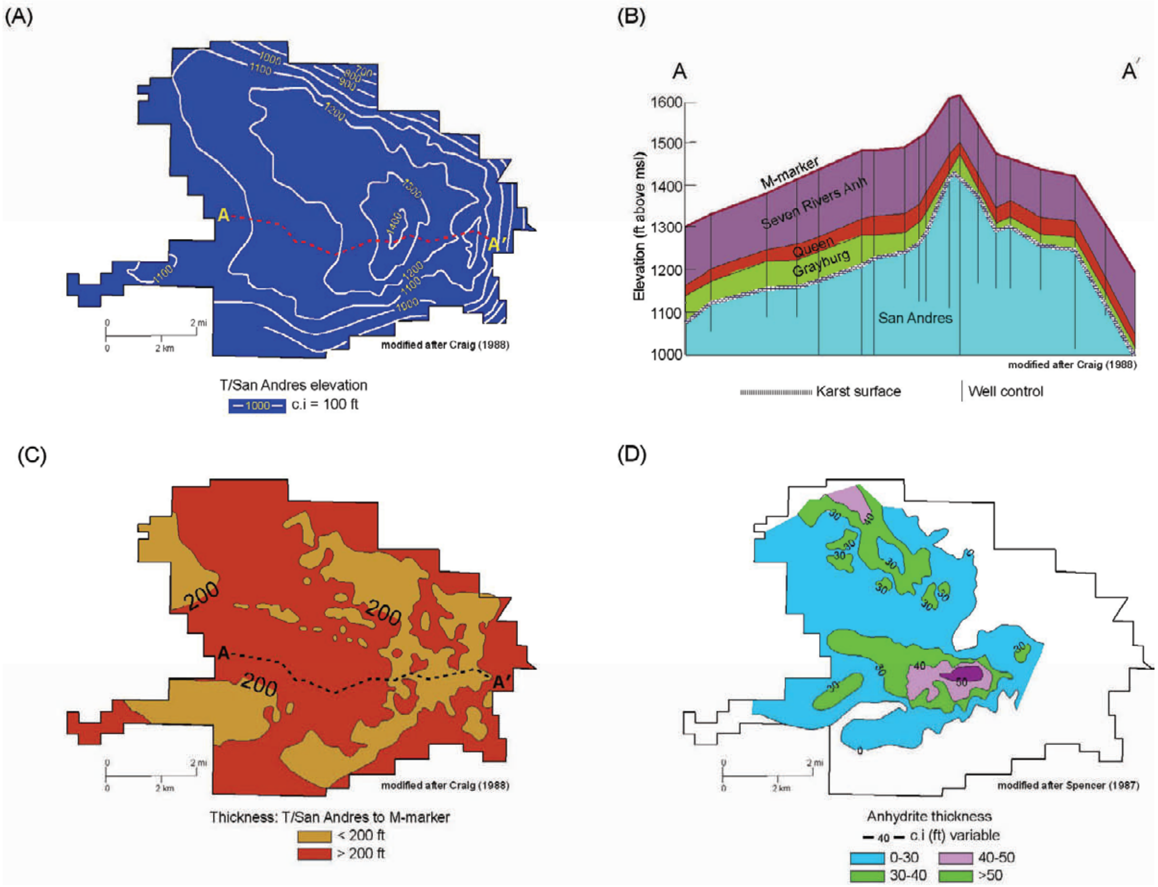

Figure 28. Yates reservoir, Pecos County: (A) U-shaped structure on top of the San Andres Formation; (B) west-east cross section A-A′ of Yates field, showing karst surface on the San Andres surface and thinning of overlying intervals onto structure (line of section shown in A and C); (C) isopach map of the interval between the San Andres top and the M-marker within the Seven Rivers Formation, showing thinning of interval onto structure; and (D) isopach map of the Seven Rivers anhydrite, showing thinning of evaporate facies onto structure, thus demonstrating control of brine-pool depth by underlying structure.

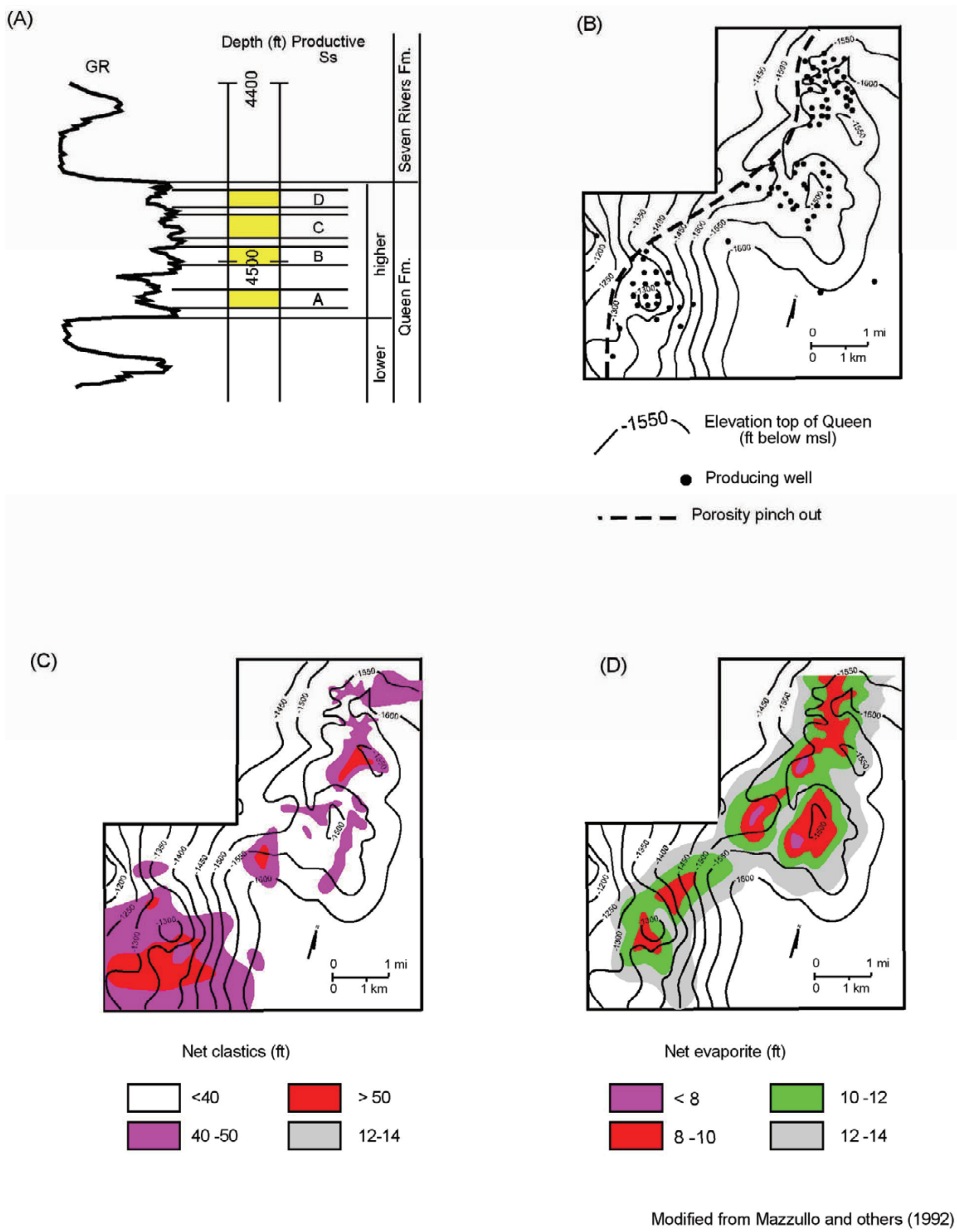

Figure 29. Concho Bluff and North Concho Bluff reservoirs: (A) representative well log of upper Queen reservoir-sandstone interval; (B) structure map on top of the Queen showing preferential locations of producing wells on structural highs or ramps downdip of porosity-pinch-out margin (shown in C); (C) net clastics map of the reservoir interval and position of the downdip margin of porosity plugging by evaporites; and (D) net evaporate map of the Queen showing thinning of evaporate facies onto structure. Modified from Mazzullo and others (1992).

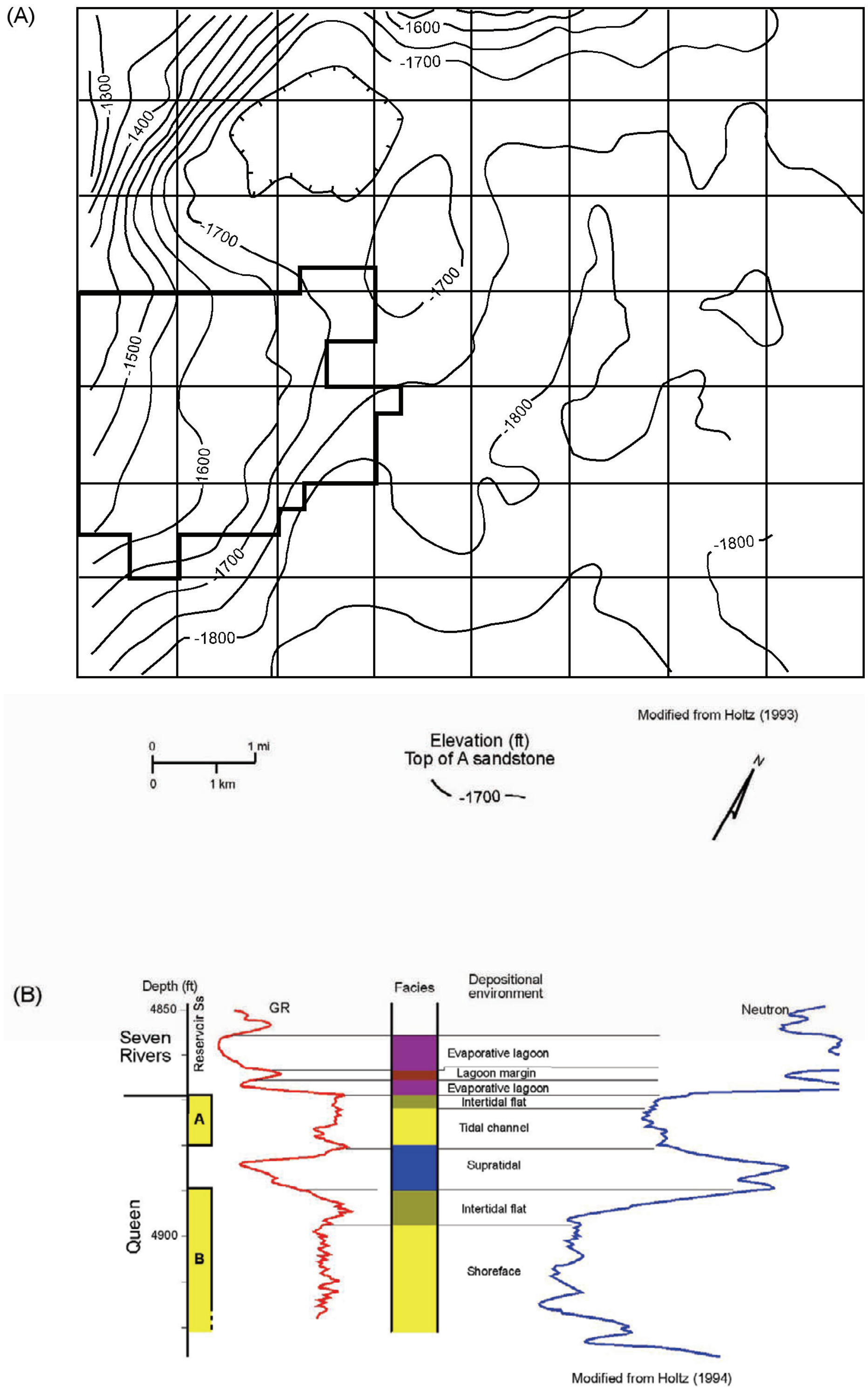

Figure 30. McFarland reservoir: (A) structure map on top of the Queen Formation; State University Units No. 1 and 2 are outlined; and (B) representative well log of the upper Queen productive-sandstone interval. Production is from interpreted tidal-channel and shoreface (probable beach ridge) sandstone. Supratidal carbonate provides baffle between productive sandstones. Modified from Holtz (1994).

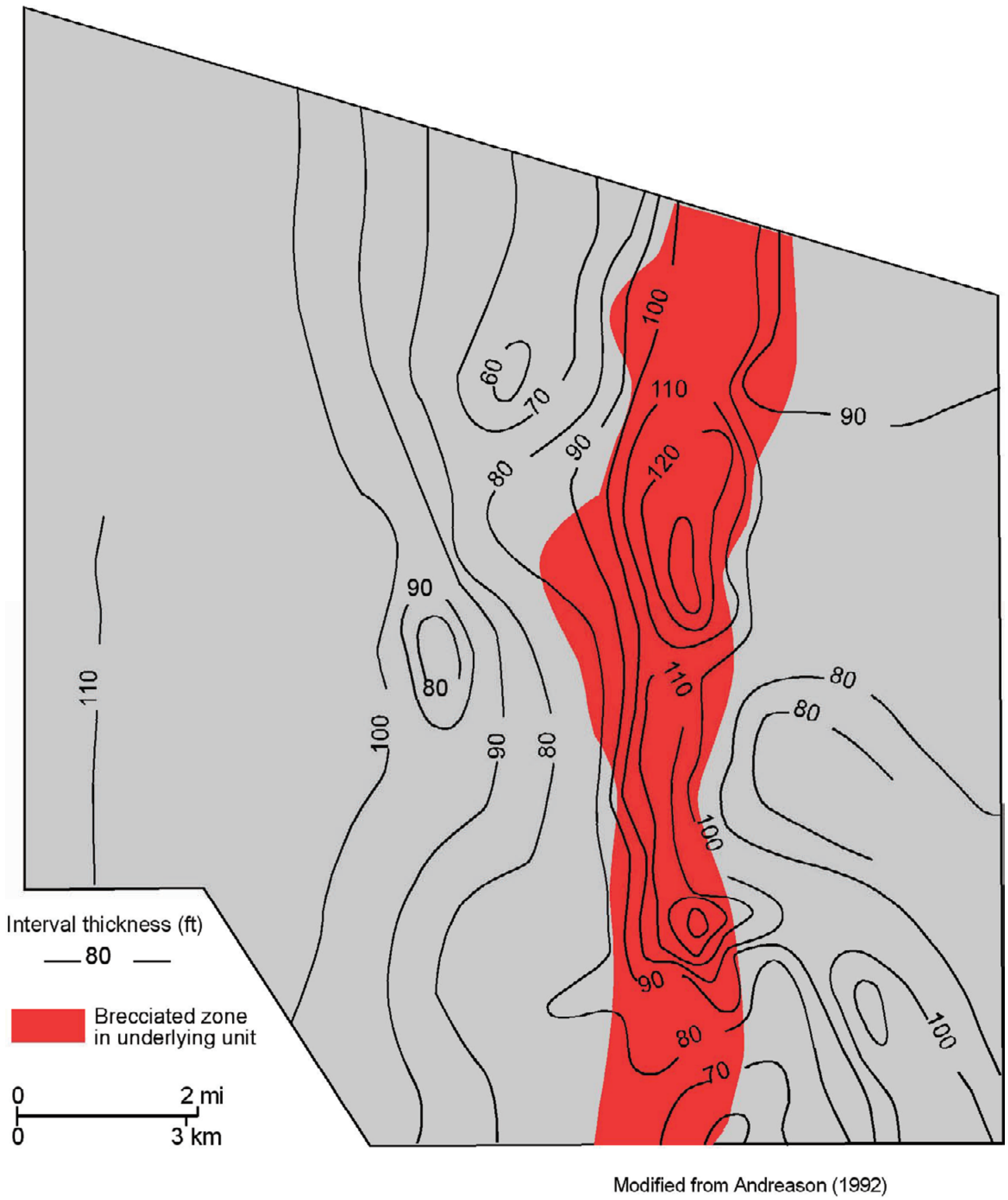

Figure 31. North Ward-Estes reservoir: isopach map of siliciclastic-dominated productive interval (fig. 12, 2,645–2,720 ft). Also shown is zone characterized by occurrences of dolostone solution breccia in underlying interval (fig. 12, 2,720–2,738 ft). Sandstone reservoir interval shows conspicuous thickening over area of solution collapse. Modified from Andreason (1992).

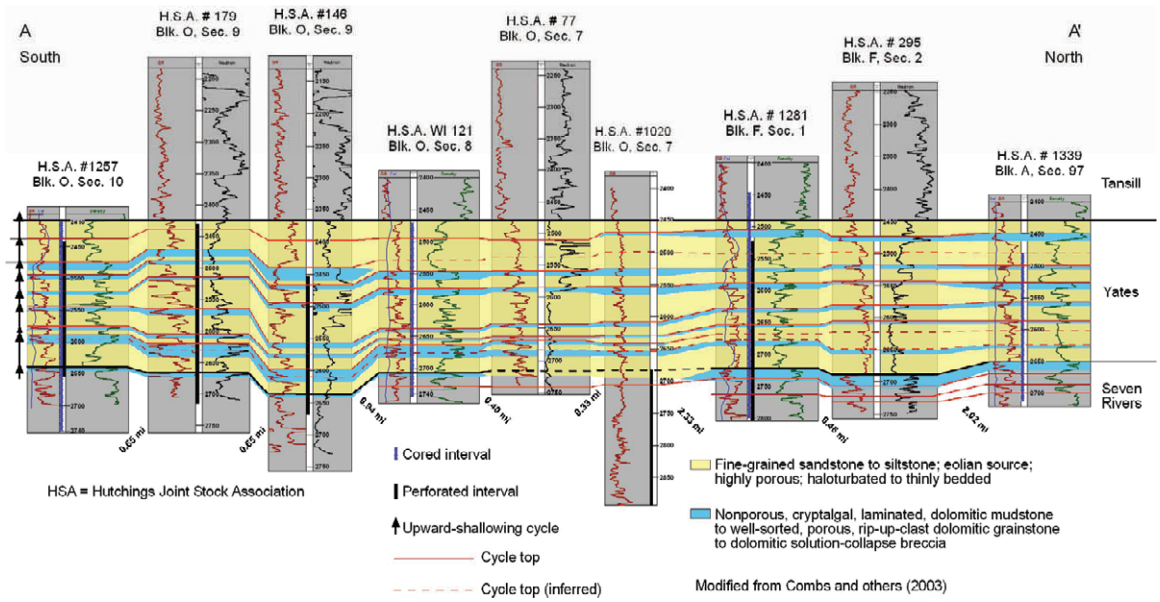

Figure 32. Strike cross section A-A′ of Yates reservoir at North Ward-Estes field, Ward County. Shown are depositional cycle boundaries and generalized rock types. Location of section shown in figure 26. Although siliciclastics had late-highstand-lowstand-phase eolian sources, their present character indicates reworking by marine processes during the transgressive phase. Modified from Combs and others (2003).

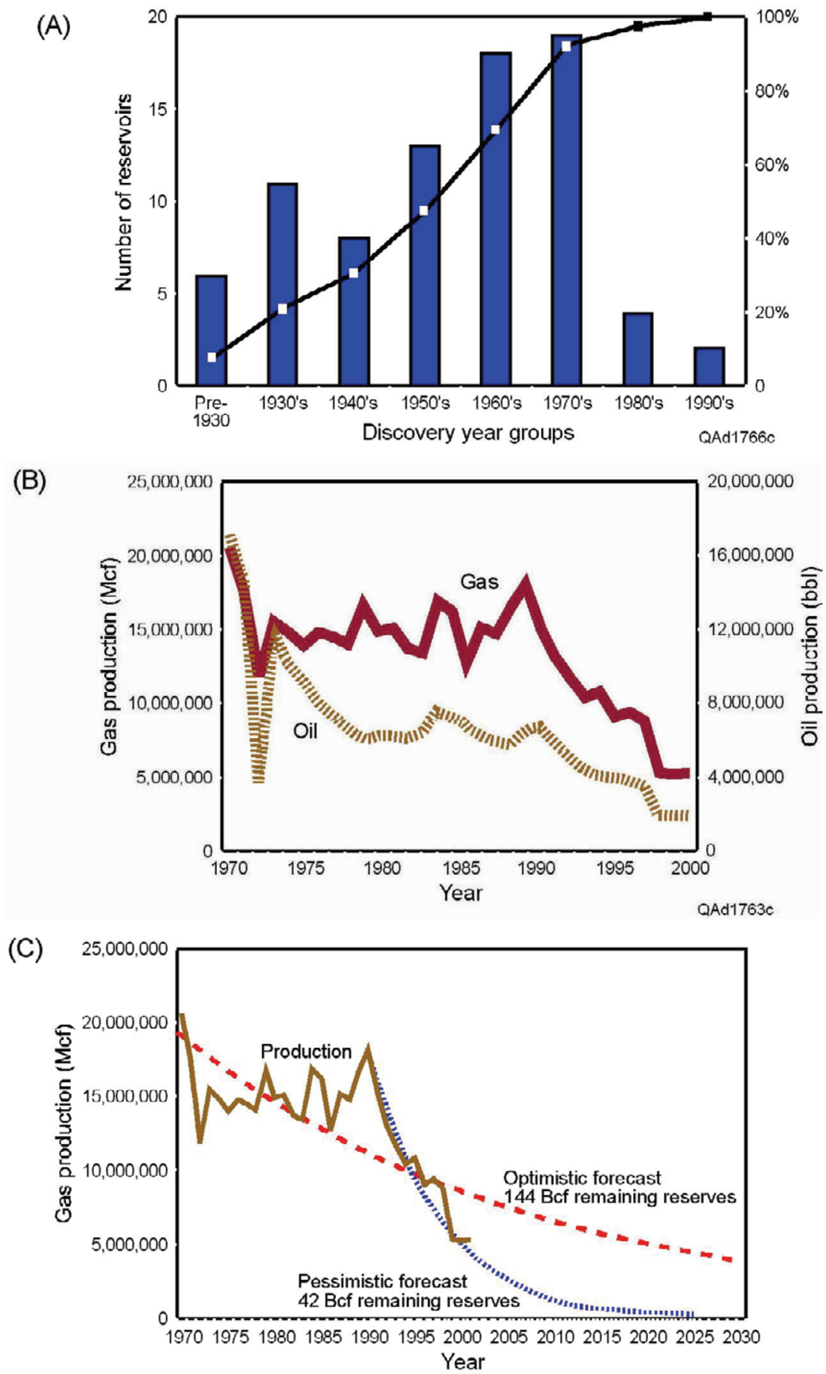

Figure 33. Histograms for Yates Formation productivity (A) new field discoveries summarized by decade showing abrupt decline since the 1970's; (B) hydrocarbon production where oil production has shown decline since the early 1970's, and gas production has shown decline since 1990; and (C) optimistic and pessimistic forecasts of gas productivity, based on reservoir performance since 1970. Optimistic forecast is based on average performance since 1979, whereas pessimistic forecast is based on declining performance since 1990. From Combs and others, 2003.