Ozona sandstone, Val Verde Basin, Texas: Synorogenic stratigraphy and depositional history in a Permian foredeep basin

H. Scott Hamlin

ABSTRACT
The Ozona sandstone is a record of Permian synorogenic sedimentation in a foreland basin. The Ozona comprises terrigenous clastic slope and basin systems overlain by mixed clastic-carbonate shelf-ramp systems. Ozona sandstones form low-permeability gas reservoirs in Crockett County, Texas. I used wire-line logs and cores to map Ozona genetic stratigraphy and to reconstruct the depositional and tectonic history during the final phase of the Ouachita orogeny. Ozona depositional systems are composed of sandy turbidite channel and lobe genetic facies enclosed in laterally extensive muddy turbidite sheets and hemipelagic drapes. Channel and lobe complexes and turbidite sheets together form basin-floor apron systems. Coeval slope systems are mud-dominated products of mass transport processes. Sediment dispersal systems evolved from point sourced to line sourced.

Ozona sequence development was primarily controlled by tectonic uplift and subsidence. Stratal geometries, facies associations, sediment input patterns, and depocenter locations are stable within sequences, but they change across sequence boundaries in response to tectonically driven changes in basin geomorphology. Onlapping stratal geometries in the lower sequence record excess accommodation space in the study area as plate convergence progressed from south to north. Offlapping strata in the middle and upper sequences formed in response to reduced accommodation space and intraforeland uplift in the north. At the base of each sequence,

ACKNOWLEDGEMENTS
I thank William Galloway, Seay Nance, Sigrid Clift, and Dee Jenkins for their guidance and support. Union Pacific Resources (now Anadarko) donated most of the well-log data. At the Bureau of Economic Geology, funding for this research was provided by the State of Texas Advanced Resource Recovery Project (STARR) and the Permian Basin Geological Synthesis Project. I gratefully acknowledge the constructive comments of peer reviewers Stephen P. Cumella, Dennis R. Kerr, Lee F. Krystinik, and AAPG editor Gretchen M. Gillis. Reviews of an earlier version of this manuscript by Jim Rogers, Michael L. Sweet, and an anonymous reviewer provided valuable guidance for preparing this final version. I thank Lana Dieterich and Amanda Masterson for copyediting the manuscript and Joel Lardon for helping with the graphics. Publication was authorized by the Director, Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin.

DATAShare 31
Figure 6 is accessible as an oversized image on the AAPG Web site as Datashare 31 (www.aapg.org/datashare/index.html).

Copyright ©2009. The American Association of Petroleum Geologists. All rights reserved.

Manuscript received September 7, 2008; provisional acceptance December 18, 2008; revised manuscript received January 7, 2009; final acceptance January 20, 2009.

DOI:10.1306/01200908121
sandstone depocenters step toward the thrust belt in response to thrust-sheet loading and foredeep subsidence, but within each sequence, depocenters migrate away from the thrust belt. Foredeep migration through time provides a predictive tool for locating Ozona reservoir analogs farther south in Val Verde Basin.

INTRODUCTION

The Ozona sandstone records the final synorogenic depositional episode during the Early Permian in the Val Verde Basin in southwest Texas (Figure 1). The Ozona interval is composed of 200–2000 ft (61–610 m) of sandstones, mudstones, and carbonates, most of which were deposited in slope and basin systems. Using wire-line logs and cores, this study was designed (1) to map Ozona genetic stratigraphy and (2) to refine our understanding of the depositional and tectonic history of the Val Verde Basin.

Slope and basin depositional systems contain important hydrocarbon reservoirs worldwide and have been a major focus of research in recent years (e.g., Weimer et al., 2000; Mutti et al., 2003a). Much progress has been made in integrating subsurface data sets to advance our understanding of deep-water reservoirs (e.g., Jennette et al., 2003; Fugelli and Olsen, 2007). Armed with these new insights, I use available subsurface data in an old petroleum province to take a fresh look at stratigraphy and depositional styles in a foredeep basin. Results presented here should be closely applicable in adjacent Midland and Delaware deep-water basins (Figure 1) and more broadly applicable in foreland settings worldwide.

The Ozona is part of the Canyon sandstone tight gas play in the Val Verde Basin. Canyon sandstones form unconventional tight gas reservoirs that have low permeabilities but are pervasively gas saturated (Dutton et al., 1993). Productivity depends more on reservoir quality than on structural position, and reservoir quality is controlled by both depositional and post depositional processes. Original porosity and permeability were mostly destroyed by compaction and by cementation with quartz and carbonate minerals (Hamlin et al., 1995; Dutton et al., 1996). Natural fractures also influence productivity (Marin et al., 1993; Hentz, 1995). Despite poor reservoir quality, Canyon sandstones have produced more than 3.5 tcf (9.9 × 10¹⁰ m³) of gas in the Val Verde Basin; Ozona field accounts for more than 40% of that gas (Railroad Commission of Texas, 2004).

Canyon sandstones comprise four distinct terrigenous clastic successions: lower Canyon, Sonora Canyon, Ozona Canyon, and Wolfcamp sandstone (Figures 1, 2). Canyon stratigraphic units are not exposed at the surface and have no formal formation designations. In this article, the term Ozona will be used to refer to the focus of this study, which is the producing interval in the Ozona gas field and is also known as Ozona sandstone, Ozona Canyon, or Canyon sand. Canyon intervals thicken toward the south but dip toward the north, owing in part to post depositional uplift and erosional truncation beneath Cretaceous carbonates (Sanders et al., 1983) (Figure 2). Depth of burial in the Ozona ranges from 2000 to 8500 ft (610 to 2591 m).

METHODS AND DATA

The Ozona study area encompasses about 800 mi² (2072 km²) in Crockett County, Texas. The database includes wire-line logs from 1300 wells and cores from 11 wells (Figure 3). I used gamma-ray, acoustic, neutron, and density logs for stratigraphic correlation and lithologic determination. Cores provided data for lithofacies description and lithologic calibration of well logs. Gamma-ray logs consistently distinguish sandstone (low gamma ray) from mudstone (high gamma ray), providing a measure of clay volume (Asquith et al., 2004). Carbonate also causes low gamma-ray responses but can be distinguished from sandstone by greater densities and acoustic velocities on porosity logs (Asquith et al., 2004).

Sandstones form the frameworks of depositional systems and the reservoirs of hydrocarbon systems. Sandstone geometries, thicknesses, and vertical bedding styles are all amenable to analysis using log and core data. Lateral continuities are characterized using interwell correlation and interpolation...
Figure 1. (A) detail map of the Val Verde Basin and (B) Index map of the Permian Basin region of west Texas. (A) Ozona and Sonora sandstones produce gas throughout their mapped extents (stippled), whereas lower Canyon and Wolfcamp gas fields are more localized as shown. Line of cross section AA′ is also shown (Figures 2, 6). Structural elements are modified from Dutton et al. (2005). Gas fields are from the Railroad Commission of Texas (2004).
techniques. Delineation of sandstone geometries and depocenters provides evidence for interpreting depositional systems, reconstructing sediment input and dispersal patterns, and timing and location of tectonic events.

Bed thickness is another relevant characteristic of Ozona sandstones. In this study, thick-bedded sandstones are defined as sandstone beds greater than 1 ft (0.3 m) thick interbedded with mudstone beds less than 0.5 ft (0.15 m) thick, whereas thin-bedded sandstones are defined as interbedded sandstone and mudstone having bed thicknesses less than 1 ft (0.3 m) thick (Figure 4). Although gamma-ray logs have a vertical resolution limit of about 2 ft (0.6 m), thinly bedded successions can be recognized by spiky trace patterns.

**Regional Setting**

The Val Verde Basin is a foredeep within the Permian Basin, which is located on the south margin of the North American plate in the foreland of the Ouachita orogenic belt (Ross, 1986; Wuellner et al., 1986; Hills and Galley, 1988) (Figure 1). The Central Basin platform, Ozona arch, and Eastern shelf are intraforeland uplifts on the north margin of the Val Verde Basin (Figures 1, 5). Prior to plate convergence, this north margin was part of an early Paleozoic divergent continental margin (Hills and Galley, 1988). During plate convergence, the north margin was periodically exposed and supplied sediment to surrounding basins (Candelaria et al., 1992). The Ouachita orogenic belt (thrust belt) formed a synorogenic convergent margin to the south (Figure 1). Allochthonous Ouachita rocks were thrust over North American basement rocks (Viele, 1989). Thrust-related uplift formed a major sediment source area to the south (Wuellner et al., 1986) (Figure 5).

Preorogenic Strawn limestone was deposited during relative tectonic quiescence in a carbonate ramp setting (Tai and Dorobek, 2003). Post-Strawn
foredeep subsidence created a large accommodation space for subsequent deep-water clastic fill (Figure 2). The first synorogenic deposition was a thin, organic-rich black shale, which overlies the Strawn and represents an extended period of starved basin conditions in the late Pennsylvanian (Rall and Rall, 1958) (Figure 2). The black shale is overlain by slope and basin strata of the Canyon intervals (Hamlin et al., 1995). The Ozona forms the uppermost part of the synorogenic fill (Figure 2).

**Figure 3.** Index map showing data used in this study. Ozona isopach contours are also shown. Cross section AA" is shown in Figures 2 and 6. Cross section AA' lies within the study area, whereas the A'A" leg extends beyond the study area, relying on a narrow corridor of wells for a more complete stratigraphic profile. Cross sections BB' and CC are shown on Figure 8, and DD' and EE' are shown on Figure 11.

**OZONA STRATIGRAPHY**

This section describes Ozona stratigraphy using a conceptual model of hierarchical, spatially related components that include both descriptive elements (lithofacies, bedding styles, sandstone geometries) and interpretive elements (genetic facies, depositional systems, sequences). Lithofacies are distinguished by bedding styles, bed thicknesses, sedimentary structures, compositions, and
Figure 4. Photographs of Ozona lithofacies examples from the core. Sandstone is light colored, and mudstone is dark colored. Core depths are shown in feet. Dark circular features are core-plug sample locations.

Figure 5. Schematic profile of the Val Verde Basin showing geomorphic elements reconstructed. The basin is bounded to the north by intraforeland uplifts and to the south by the Ouachita thrust belt (Wuellner et al., 1986).
Figure 6. North–south stratigraphic dip cross section AA′ showing gamma-ray logs, lithologies, genetic units, depositional systems, sequences, and stratal geometries. The line of section is located in Figures 1 and 3. For an oversized image of this figure see Datashare 31 (www.aapg.org/datashare/index.html).
textures as described from the core. Genetic facies are the deposits of specific depositional environments (Galloway and Hobday, 1996). Genetic facies interpretation is based on lithofacies composition, external geometries, and internal bedding architecture. Genetic facies are similar to depositional elements (Mutti and Normark, 1991; Posamentier and Kolla, 2003). Depositional systems are composed of contiguous process-related suites of genetic facies (Fisher and McGowen, 1967).

I subdivided the Ozona into three sequences and eight genetic units (Figure 6). Ozona sequences group genetically related depositional systems and are bounded by continuous, mappable surfaces. Genetic units group correlative sandstone facies that are bounded by laterally continuous mudstone facies. Ozona sequences and genetic units form approximate chronostratigraphic units, which are useful for reconstructing depositional history.

Figure 7. Net sandstone isolith map of genetic unit H, lower Ozona sequence. Cross section AA' is shown in Figure 6, and cross section BB' is shown in Figure 8a. Shelf margin and slope lapout positions are based on stratal geometries (Figure 6).
Regional Sandstone Attributes

Locations, geometries, vertical bedding styles, and stratal relationships of large (mile [kilometer] scale) sand-rich features are basic descriptive data essential for depositional and sequence-stratigraphic interpretation. Ozona genetic units were first recognized as distinctive and traceable stratigraphic intervals using Figure 8.

Figure 8. Detailed gamma-ray log cross sections through lower sequence genetic units (a) H and (b) F. Note the horizontal scale differences. The lines of section are located in Figures 3, 7, and 9. Wells are identified by API number (42-105-xxxx). Colors are used to highlight correlations.
well-log correlations. This section describes Ozona genetic units as a basis for interpretation in subsequent sections.

The lower Ozona sequence comprises three genetic units composed of thin-bedded sandstone and mudstone and thick-bedded sandstone (Figure 6). Genetic unit H consists of lobate sandstone depocenters that extend into the study area from the south and southwest (Figure 7). Sandstones in genetic unit H thin and become more thinly bedded toward the northeast (Figure 8a). Genetic unit G displays similar patterns but includes less sandstone than does genetic unit H. Both genetic units H and G include sandstones that lie close to the lapout line on the north slope (Figures 6, 7). Genetic unit F forms two elongate depocenters that extend northeast into broad lobes of thinner sandstone (Figure 9). Individual sandstones thin and become more thinly bedded away from the northeast-oriented axis (Figure 8b).

Figure 9. Net sandstone isolith map of genetic unit F, lower Ozona sequence. Cross section AA' is shown in Figure 6, and cross section CC' is shown in Figure 8b. Shelf margin and slope lapout positions are based on stratal geometries (Figure 6).
The middle Ozona sequence encompasses four genetic units composed of lenticular sandstones (Figure 6). As in the lower sequence, middle-sequence sandstones form northeast-elongate depocenters, but unlike the lower sequence, individual middle-sequence sandstones commonly display northwest elongation (Figure 10). Most middle-sequence sandstones are small channel-form and lobate bodies that thin or pinch out between closely spaced wells (Figure 11a). Middle-sequence sandstones are separated from the slope lapout line in the north by a broad zone of homogeneous mudstone, which produces subdued baseline gamma-ray responses (Figure 6).

The upper Ozona sequence includes sandstone only in the lower part (genetic unit A); the upper part is composed of carbonate and mudstone (Figure 6). Compared with middle-sequence sandstones, genetic unit A includes more lobate sandstone geometries and extends over a larger area (Figure 12),
Figure 11. Detailed gamma-ray log cross sections through (a) middle sequence genetic units and (b) upper sequence genetic unit A. Note horizontal-scale differences for (a) discontinuous channels and (b) more continuous lobes. The lines of section are located in Figures 3, 10, and 12. Wells are identified by API number (42-105-xxxx). Colors are used to highlight correlations.
and individual sandstones are more laterally continuous (Figure 11b). The upper sequence includes separate sandstone depocenters in the north (Figure 12) and is the first Ozona sequence to extend onto the north shelf margin (Figure 6).

**Lithofacies**

Ozona lithofacies are mostly descriptive, although some successions of sedimentary structures, such as turbidites, have interpretive implications (Pickering et al., 1989). Ozona cores are composed of four main lithofacies: thick-bedded turbidites, thin-bedded turbidites, mudstone, and conglomeratic mudstone (Table 1).

Ozona thick- and thin-bedded sandstones (Figure 4) closely resemble the deposits of mixed sand and mud turbidity currents (Bouma, 1962; Pickering et al., 1989). The Bouma sequence of sedimentary structures effectively characterizes
both thick- and thin-bedded turbidites in the Ozona. In thick-bedded turbidites, Bouma divisions Tr and Tb are preferentially preserved; in thin-bedded turbidites, Bouma divisions Tcde are most common (Table 1).

Mud-dominated lithofacies in the Ozona include mudstone and conglomeratic mudstone (Table 1). Mudstones include finely laminated silt and clay (Bouma Tde) and organic-rich claystone. Conglomeratic mudstones are composed of unsorted sand and gravel suspended in a mud matrix. The largest clasts measurable in the core are slabs of sandstone and limestone 1 ft (0.3 m) long.

**Genetic Facies**

Ozona depositional systems are composed of sandy turbidite channel and lobe genetic facies enclosed in laterally extensive muddy turbidite sheets and hemipelagic drapes. Channel-levee facies flank many channel sandstones. Mass transport complexes are probably common, but their distribution is poorly documented.

Channel-fill genetic facies are composed mostly of thick-bedded turbidites (Table 2). Individual channels are mappable in the middle sequence (Figure 10), and in the lower sequence, genetic unit F includes larger channels (Figure 9). Ozona turbidite channels are primarily depositional, although channel-base erosion occurs locally (Figure 11a).

Turbidite lobe genetic facies are sandstone dominated but are more variable in bedding style than are channels (Table 2). Lobes can be distinguished from channels by their lobate geometries and lateral continuities of individual sandstones (Figure 11b). Lobe sandstones are commonly more thin bedded than channel sandstones (Figure 8a).

Ozona turbidite channels are commonly enclosed in lobes or distally attached to lobes, forming channel-lobe complexes. On sandstone isolith maps, channel-lobe complexes are characterized by a close association between channel-form and lobate geometries (Figures 7, 12). Ozona channel-lobe complexes resemble frontal-splay or distributary complexes (Posamentier and Kolla, 2003), in which both channel-fill and overbank sandstones coalesce.

Where channels are not enclosed in lobes, channel-levee facies can be identified. Thick-bedded turbidite sandstones along the channel axis grade laterally into thin-bedded, mixed sandstone and mudstone successions on the channel margins (Figure 8b). Many channels display gradational lateral contacts (Figure 11a), which by analogy...
with modern turbidite channel systems (Clark and Pickering, 1996) are channel-levee facies.

Turbidite sheet genetic facies are composed of mud-dominated, thin-bedded turbidites, forming laterally continuous successions of thinly bedded mudstone, sandstone, and local limestone (Table 2). Muddy turbidite sheet facies are identified by spiky gamma-ray responses (Figure 6).

Hemipelagic mudstones form homogeneous condensed sections. In the Ozona, hemipelagic drapes occur as thin, laterally continuous, high-gamma-ray intervals separating channel-lobes complexes. Hemipelagic facies can commonly be distinguished from muddy turbidite sheet facies by more subdued gamma-ray responses, reflecting the lack of sandy thin beds.

Mass transport complexes are composed primarily of mudstone and conglomeratic mudstone (Table 2). Most cored examples of conglomeratic mudstone are less than a few feet (1 m) thick, although one core includes a 50-ft (15-m) interval of conglomeratic mudstone in genetic unit B in a base-of-slope position.

### Depositional Systems

Ozona depositional systems formed in deep-water slope and basin-floor geomorphic settings. Ozona sandstones extend directly away from the thrust belt, but they are subparallel to the Ozona arch (Figure 1). The Ozona interval is thickest to the southwest and along a northeast-oriented trend that lies within the study area (Figure 3). From isopach patterns and sandstone distribution, I infer that a topographically low area on the basin floor extended northeast through the study area, paralleling the shelf margin in the north and forming an axis of subsidence.

Mud-dominated slope systems overlie Strawn limestone along the north margin of the basin (Figure 6). Slope mudstones can be distinguished from their basin-floor counterparts by lateral discontinuity of surfaces. In slope mudstones, gamma-ray log patterns can rarely be correlated between closely spaced wells. Slope mudstones include local bodies of sandstone and limestone, although most coarse sediment was bypassed to the basin.
Excavation and remobilization processes are most likely responsible for lateral discontinuity in Ozona slope systems, and mass transport complexes are probably the dominant genetic facies.

Pre-Ozona slope systems drape the underlying carbonate slope over a disconformable sequence boundary (Figure 6). In the middle Ozona sequence, however, slope mudstones extend out across underlying basin-floor systems in an apparent offlap wedge (Figure 6).

Ozona basin-floor systems include muddy turbidite sheets and sandy channel-lobe complexes. In the study area, thin-bedded turbidite sheets are best developed in pre-Ozona strata but are also common in the lower Ozona sequence, where they aggrade the basin floor and onlap the slope (Figure 6). In the middle sequence, turbidite sheets are mostly restricted to the southern part of the study area.

Channel-lobe complexes in the middle and upper sequences coalesce laterally to form constructional onlap-offlap aprons on the basin floor at the base of the north slope. Unlike submarine canyon and fan systems, apron systems form strike-elongate deposits fed from multiple points along the shelf margin (Reading and Richards, 1994; Galloway, 1998). Patterns of sandstone distribution suggest that the south margin formed the primary source area for channel and lobe sandstones in the middle sequence (Figure 10), whereas those in the upper sequence were probably sourced from both margins (Figure 12). Channel-lobe complexes in the lower sequence display patterns of sandstone distribution suggestive of point sources to the southwest (Figures 7, 9).

Ozona slope and basin systems display features in common with modern turbidite systems of the Ebro delta-fed apron in the Mediterranean Sea (Alonso and Maldonado, 1990; Nelson and Maldonado, 1990). Slope facies are discontinuous and mud dominated. Sand-filled channels and lobes coalesce to form strike-elongate bodies at the base of the slope and on the adjacent basin floor. Stratigraphic architecture comprises mixed offlap, onlap, and aggradation.

Genetic unit F in the lower sequence is unique in the Ozona for the scale and orientation of its turbidite channel facies. The main channel belt averages 4 mi (6.4 km) wide and 180 ft (55 m) thick and is composed of stacked channel and levee facies extending down the basin axis (Figures 8b, 9). Paleocurrents commonly parallel the basin axis in foredeep basins (Mutti et al., 2003b). Genetic unit F is probably a foredeep axial channel system similar to the Tertiary Puchkirchen Formation channel belt in the Austrian Molasse Basin (De Ruig and Hubbard, 2006).

Shelf-ramp depositional systems are confined to the upper Ozona sequence where the steep carbonate slope has been buried by middle sequence progradation (Figure 6). Genetic unit A includes a delta system consisting of small lobate sandstone bodies in a shelf-margin or outer-ramp setting (Figure 12). The basinward facies tract consists of deltaic sandstone to slope mudstone to turbidite sandstone. The upper part of the upper sequence comprises thin-bedded carbonate and mudstone in a shelf setting (Figure 6).

Sequences

Most Ozona sandstones were deposited beyond the shelf margin in lowstand systems tracts. Highstand systems tracts are represented mainly by mudstone-dominated facies, especially hemipelagic condensed sections. Hemipelagic facies record slow sedimentation in the basin and are overlain by turbidite sandstones, marking the onset of high sedimentation rates and lowstand deposition in the basin. Sequence boundaries typically lie at the contacts between hemipelagic facies and overlying turbidite facies. As used here, lowstand and highstand refer to relative sea level positions that must be inferred because of lack of direct evidence (Posamentier and Kolla, 2003). Nevertheless, the conceptual model fits Ozona successions of turbidite sandstones punctuated by hemipelagic mudstones.

The lower Ozona sequence is composed of basin-floor depositional systems. Turbidite sandstones in the lower sequence overlie thousands of feet of mudstone-dominated basin-floor systems. The lower part of the lower sequence comprises widespread turbidite sheets and lobes (genetic units H and G), whereas the upper part is more...
channelized and confined (genetic unit F) (Figure 6). The lower sequence onlaps a relatively steep (average $3^\circ$) carbonate slope about 1000 ft (305 m) below the contemporaneous shelf margin.

The middle Ozona sequence is composed of slope and basin-floor depositional systems. The slope progradational offlap becomes a factor in the middle sequence, probably in response to aggradational shoaling of the basin floor and sediment (mostly mud) input from the north. On the basin floor, turbidite channel-levee complexes are sourced primarily from the south and are prevented from extending farther north by the offlapping wedge of slope mudstone (Figure 6).

The upper Ozona sequence includes basin-floor turbidites, shelf-margin deltas, and ramp carbonates overlain by shelf carbonates and terrigenous mudstones. Shelf bypass in the lower and middle sequences changes to shelf aggradation and progradation in the upper sequence (Figure 6). Sandstone geometries and the arrangement of depositional systems indicate that perhaps for the first time, sandy sediment was entering the basin from the north (Figure 12).

By late synorogenic time, the Val Verde Basin was relatively shallow, and water depths decreased as basin filling progressed. I estimated water depths by tracing depositional surfaces from shelf to basin floor and then decompacting sediment thicknesses using simple porosity restorations (Magara, 1976). Water depths were approximately 1215–810 ft (370–247 m) for the lower Ozona sequence, 810–540 ft (247–165 m) for the middle Ozona sequence, and less than 540 ft (165 m) for the upper Ozona sequence. Sufficient slope relief remained for gravity mass transport even in the relatively shallow basin of the upper sequence, as attested to by turbidites and conglomeratic mudstones in cores.

**DISCUSSION**

**Sequence Stratigraphy**

Depositional architecture, sediment input, and depocenter location were key criteria for subdividing the Ozona into sequences (Figure 13). Sediment input for sandstones in the lower sequence, for example, was from the southwest through relatively narrow point sources, whereas sediment input in the middle sequence came mainly from the southeast through extended linear sources (Figure 13). Within each sequence, sandstone depocenters migrated northeastward along the basin-floor axis but stepped back to the south and southwest across sequence boundaries (Figure 13).

Genetic facies associations instead of specific vertical successions characterize Ozona sequences. In the lower sequence, turbidite lobes are overlain by leveed channels, a succession commonly related to late falling and early rising phases of relative sea level change (Posamentier and Kolla, 2003), but in the middle sequence, turbidite lobes are best developed in the upper part of the sequence (Figure 13). Facies associations, however, are distinctive: the lower sequence comprises laterally continuous lobes and large channels, the middle sequence comprises small discontinuous channels and lobes, and the upper sequence includes both turbidite and deltaic sandstone facies (Figure 13).

In foredeep basins, alternating periods of tectonic uplift and subsidence mostly control cyclicity and sequence development (Mutti et al., 2003b). Eustatic controls on late Paleozoic sequences are recognized on stable cratonic platforms, but in adjacent orogenic basins, eustatic controls are not easily separated from tectonic controls (Ross and Ross, 1988). Thick successions of deep-water depositional facies in Ozona and underlying Canyon intervals indicate that the Val Verde Basin was an underfilled foredeep (Sinclair, 1997), where accommodation space was little constrained by eustasy.

Ozona sequences are primarily responses to tectonic events that controlled pulses of uplift in the source area (sediment supply) and related subsidence in the adjacent foredeep. Basin geomorphology remained relatively stable between tectonic events but was rearranged after each tectonic event. Consequently, Ozona sequences are characterized by distinctive sediment dispersal and depositional systems that change across sequence boundaries (Figure 13).
Figure 13. Characteristic features of Ozona sequences. Sandstone isolith maps compare channel and lobe geometries of selected genetic units (A, B, E, F, H). The basin-floor axis coincides with the Ozona maximum thickness trend (Figure 3), which probably delineates a syndepositional axis of maximum subsidence. The basin-floor axis, which is identical on all sandstone maps, also serves as a reference line. Sediment input arrows are based on sand-body elongation, thickening directions, and facies associations.
Stratigraphic Implications for Tectonic Events

Early synorogenic strata, represented by the black shale condensed section, record starved basin conditions that developed after foredeep subsidence but before significant influx of sediment eroded from the thrust belt (Figure 14). Delayed filling is common in foreland basins and may result from the rate of subsidence outpacing the rates of sediment erosion, transport, and deposition (Flemings and Jordan, 1990). In the Ozona study area, much of the lag time results from infilling asymmetrically from the south as the foredeep migrated northward in response to plate convergence.

Variations in stratigraphic thickness have been used to document Permian Basin tectonic history, to analyze subsidence patterns, and to infer lithospheric response to thrust-sheet loading (Yang and Dorobek, 1995). Depositional geometries (stacking patterns), however, provide additional evidence for documenting the timing and location of tectonic deformation and can be used to refine reconstructions of tectonic history. Basin-floor aggradation and slope onlap, dominating the synorogenic fill up to the lower Ozona sequence, indicate that deposition lagged subsidence and the basin remained underfilled (excess accommodation space) (Figure 14). Progradational offlap in the middle and upper sequences is a response to shoaling (reduction of accommodation space) and uplift on the north margin of the basin (Figure 14).

Sandstone distribution patterns also provide information useful for reconstructing tectonic history. Changes in locations of sand deposition, in transport directions, and in source areas reveal a more detailed history of episodic thrusting and intrabasinal uplift than do gross thickness changes alone. Sand is a sensitive indicator because (1) an extrabasinal source is commonly needed to supply large volumes of sand to the basin floor (Galloway, 1989) and (2) sand transport and deposition are more focused and confined relative to mud. Thus, sandy deposits on the basin floor are more reliably traced back to tectonic events in source areas.

Stratigraphic modeling of foreland basins suggests that facies generally prograde in the direction of thrust movement but step back toward the thrust front at the onset of thrusting events (Flemings and Jordan, 1990). Similarly, across Ozona sequence boundaries, sandstone depocenters step abruptly toward the thrust belt, but within sequences, depocenters shift gradually back to the north (Figures 13, 14). At the onset of thrusting, accommodation space is created faster than sediment can be supplied to the basin, and depocenters shift toward the axis of subsidence. As thrust activity diminishes, deposition catches up with subsidence, and depocenters extend beyond the axis of subsidence (Flemings and Jordan, 1990). Ozona sequence boundaries, therefore, most likely record the onset of thrusting events. Hemipelagic mudstones that underlie sequence boundaries were deposited (in part) during initial pulses of loading-induced subsidence.

Implications for Exploration

In the Val Verde Basin, the relationship between stratigraphy and tectonics provides a useful tool for exploration. Although the Ozona is a mature target and its distribution to the south is limited by erosional truncation, older Canyon intervals probably display similar responses to tectonic events and include similar depositional systems. Most Ozona sandstones are confined to a linear trend corresponding to the syndepositional axis of maximum subsidence, which migrated northward through time. Thus, successively older intervals should contain linear trends of maximum sandstone progressively farther to the south. Although these pre-Ozona sandstones will be encountered at increasing depths southward, depth of burial is lessened by postdepositional uplift (Figure 2).

The Ozona play concept (linear trends of sandstone in syndepositional foredeeps) is especially valid for Val Verde County. To the west in Terrell County, Wolfcamp gas production is related to thrusting structures (Montgomery, 1996), and to the east in Edwards County, production is mainly an extension of the Sonora trend of slope sandstones adjacent to the Eastern shelf (Hamlin et al., 1995) (Figure 1). Deep wells reveal the presence of thick sandstones in Val Verde County north of the thrust belt, but established production is limited (Figure 1). Although reservoir quality may be poor,
<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Tectonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offlap</td>
<td>Final thrusting event in south</td>
</tr>
<tr>
<td>Carbonate ramp</td>
<td>Decreasing uplift in the north</td>
</tr>
<tr>
<td>Turbidite channel-lobe complexes</td>
<td></td>
</tr>
<tr>
<td>Offlap</td>
<td>Thrusting event and uplift in the south</td>
</tr>
<tr>
<td>Muddy slope</td>
<td>Intraforeland uplift in north</td>
</tr>
<tr>
<td>Turbidite channel-lobe complexes</td>
<td></td>
</tr>
<tr>
<td>Onlap</td>
<td>Foredeep in study area</td>
</tr>
<tr>
<td>Turbidite sheets</td>
<td>Thrusting event and uplift in the south</td>
</tr>
<tr>
<td>Turbidite channel-lobe complexes</td>
<td></td>
</tr>
<tr>
<td>Onlap</td>
<td>Continued subsidence</td>
</tr>
<tr>
<td>Turbidite sheets</td>
<td>Foredeep migrating toward study area</td>
</tr>
<tr>
<td>Hemipelagic facies</td>
<td></td>
</tr>
<tr>
<td>Starved basin</td>
<td>Initial subsidence</td>
</tr>
<tr>
<td>Condensed section</td>
<td>Foredeep south of the study area</td>
</tr>
<tr>
<td>Hemipelagic facies</td>
<td></td>
</tr>
<tr>
<td>Passive margin</td>
<td>Preorogenic</td>
</tr>
<tr>
<td>Carbonate ramp</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 14.** Schematic profiles representing successive depositional-tectonic episodes in the northern part of the Val Verde Basin: (a) late preorogenic passive margin carbonate ramp, (b) early synorogenic starved basin, (c) pre-Ozona mudstone-dominated onlap wedge, (d) lower Ozona sequence basin-floor aggradation and slope onlap, (e) middle Ozona sequence progradational offlap, and (f) upper Ozona sequence late synorogenic offlap and reestablishment of carbonate ramp. Deep-water accommodation space was initially created and then progressively filled by migration of the thrust belt toward the study area. Renewed thrusting and relocation of sandstone depocenters mark the beginning of each Ozona sequence.
lower Canyon gas production will probably be extended farther south and west in Val Verde County.

CONCLUSIONS

Principal Ozona sandstone depositional systems are turbidite channel-lobe complexes arranged in point- and line-sourced, onlap-offlap aprons at the base of the north slope of the synorogenic Val Verde foreland basin. Channel and lobe genetic facies are distinguished by sandstone geometries and continuities and internal bedding styles. Turbidite sandstones are concentrated along axes of maximum subsidence that coincide with syndepositional foredeeps. Northward foredeep migration through time provides a predictive tool for locating similar sandstone maxima in underlying Canyon intervals.

Successions of turbidite sandstones punctuated by hemipelagic mudstones define Ozona sequences. Instead of specific vertical facies successions, Ozona sequences are characterized by lateral facies associations, sediment dispersal patterns, and depocenter locations, which reflect geomorphic stability between tectonic events. Ozona sequence development was primarily controlled by tectonic uplift and subsidence. Stratigraphic response to eustasy is not apparent, perhaps because the basin remained underfilled for most of the synorogenic period.

Syndepositional tectonic events can be inferred from stratigraphic architecture, sandstone distribution, and sequence development. Offlap and onlap stratal geometries track foredeep migration as plate convergence progressed from south to north. Sandstone geometries and depositional systems point toward source areas linked to uplift in the thrust belt or intraforeland areas. Sequence boundaries are marked by systematic shifting of sandstone depocenters in response to episodic thrusting events.

REFERENCES CITED


