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Role of sea-level change in deep water deposition along a carbonate shelf margin, Early and Middle Permian, Delaware Basin: implications for reservoir characterization

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Abstract: The architecture and sedimentary characteristics of deep water deposition can reflect influences of sea-level change on depositional processes on the shelf edge, slope, and basin floor. Outcrops of the northern slope and basin floor of the Delaware Basin in west Texas are progressively exposed due to canyon incision and road cutting. The outcrops in the Delaware Basin were measured to characterize gravity flow deposits in deep water of the basin. Subsurface data from the East Ford and Red Tank fields in the central and northeastern Delaware Basin were used to study reservoir architectures and properties. Depositional models of deep water gravity flows at different stages of sea-level change were constructed on the basis of outcrop and subsurface data. In the falling-stage system tracts, sandy debris with collapses of reef carbonates are deposited on the slope, and high-density turbidites on the slope toe and basin floor. In the low-stand system tracts, deep water fans that consist of mixed sand/mud facies on the basin floor are comprised of high- to low-density turbidites. In the transgression and high-stand system tracts, channel-levee systems and elongate lobes of mud-rich calciturbidite deposits formed as a result of sea level rise and scarcity of sandy sediment supply. For the reservoir architecture, the fan-like debris and high-density turbidites show high net-to-gross ratio of 62 %, which indicates the sandiest reservoirs for hydrocarbon accumulation. Lobe-like deep water fans with net-to-gross ratio of 57 % facilitate the formation of high quality sandy reservoirs. The channel-levee systems with muddy calciturbidites have low net-to-gross ratio of 30 %.

Key words: sea level change, deep water fans, reservoir architecture, carbonate shelf margin, Delaware Basin.

Introduction

The Delaware Basin is the westernmost sub-basin in the Permian Basin which is one of the richest hydrocarbon basins in the United States. The north-northwest-trending Delaware Basin was bordered to the north by the Guadalupe Mountains, to the west by the Diablo Platform, to the south by the Marathon Fold Belt, and to the east by the Central Basin Platform (Fig. 1). Up to 2009, nearly 30 billion barrels of oil had been produced from approximately 106 billion barrels of oil originally contained in the Permian Basin (Ruppel 2009). As one of the significant components in the Permian Basin, the Delaware Basin hosts many economically important hydrocarbon reservoirs (Nance 2009). The Bone Spring Formation (Leonardian in the Lower Permian) primarily consists of lime-mudstone, calciturbidites and debris flow deposits. The dark-lime mudstone/wackstone acted as a source rock interval (Justman & Broadhead 2010), and the turbidites and debris provide reservoirs for hydrocarbon in the slope area of the basin. The Delaware Mountain Group — DMG (Guadalupian in the Middle Permian) consisting of thick, mixed siliciclastic/carbonate slope and basin floor strata is the major reservoir in the Delaware Basin. Oil and gas have been produced from the siliciclastic/carbonate dominated facies in the Cutoff, Brushy Canyon, Cherry Canyon and Bell Canyon Formations with depth ranging from 274 m to 2993 m. The stratigraphy, sedimentary facies and reservoir characteristics of these deep water deposits have been studied extensively both in their outcrops in the Guadalupe Mountains (Gardner 1992, 1997; Fitchen 1993; Kerans & Kempter 2002; Ruppel et al. 2002; Janson et al. 2007; Amerman 2009) and subsurface (Barker & Halley 1986; Montgomery 1997; Dutton & Flanders 2001; Dutton et al. 2003; Gardner et al. 2003; Asmus & Grammer 2013). Despite the economic significance of the Bone Formation and DMG, most researches regarding their stratigraphy, lithology, and reservoir characteristics were derived from geographically severely limited outcrop exposures and a few field locations (Nance 2009). Due to the relatively smaller extent of oil and gas production in the western part of the Delaware Basin, integrated study combining outcrop analogue and subsurface data is significant for exploring and predicting the effective reservoirs.

The character of sedimentation in basins is related to the dynamic processes and feedback mechanisms between the external (allogenic) and internal (autogenic) forcings that govern sediment dispersal in depositional systems (Stow et al. 1985; Richards et al. 1998; Castelltort & Van Den Driessche 2003; Allen 2008; Sømme et al. 2009; Bourget et al. 2010). Sea level change, one of the external forcings, is an important parameter influencing the stratigraphic succession and resulting sedimentary architecture in deep water depositional systems (Perlmutter & Matthews 1990; Posamentier &

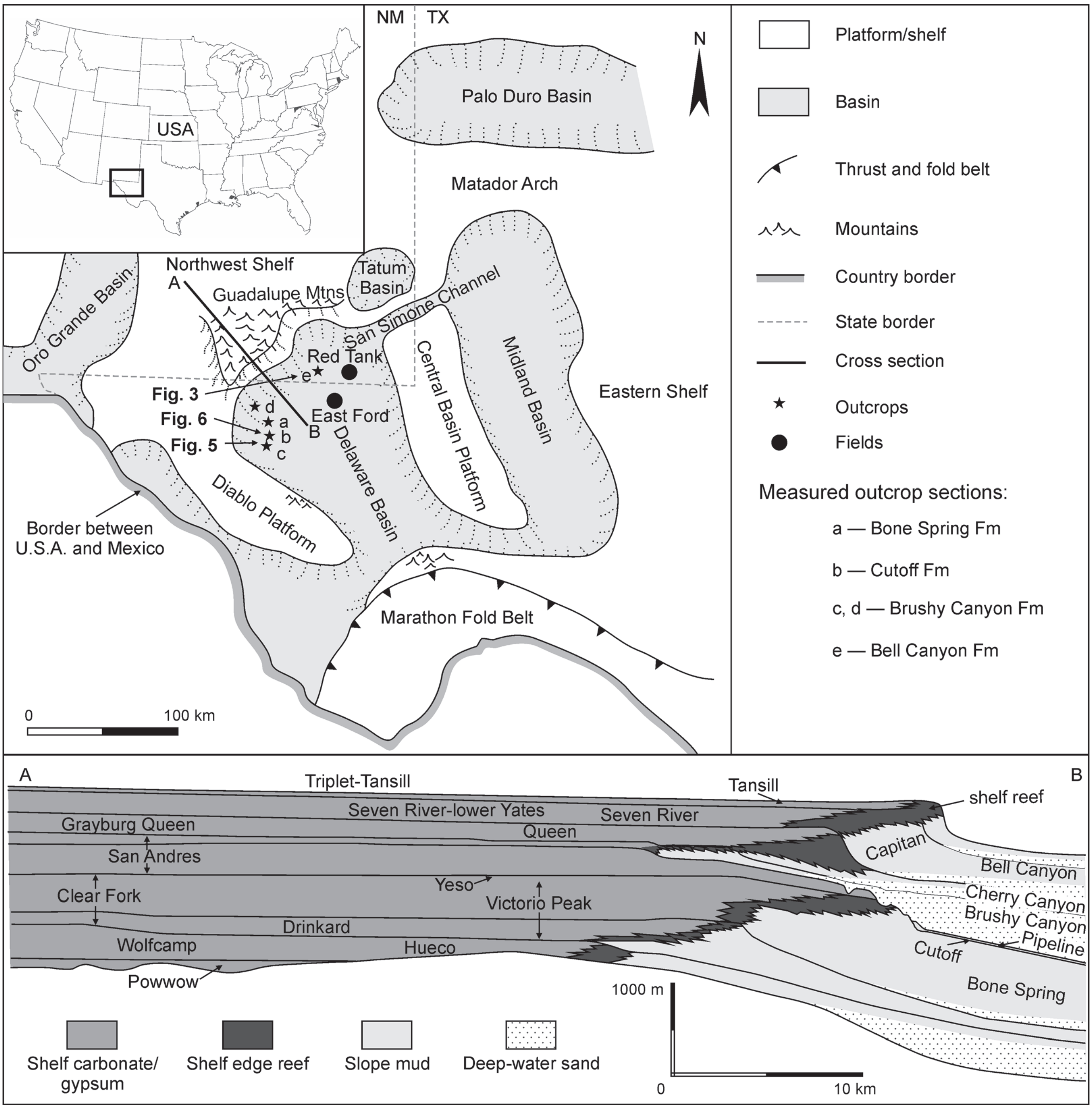

Fig. 1. Regional map showing general paleogeography of the Permian Basin and schematic stratigraphy of the Lower and Middle Permian in the Delaware Basin, adapted from (Sonnenfeld 1993; Kerans 1995).

Kolla 2003; Kamberis et al. 2005; Steel et al. 2008). Sequence stratigraphic relationships in the Delaware Mountains were investigated and described by (Gardner 1992, 1997) and (Kerans & Kempter 2002). Patterns of siliciclastic and carbonate sedimentation record the effects of sea level changes. In a falling stage system tract, forced regression of the shoreline was caused by rapid sea level fall (Catuneanu 2006; Catuneanu et al. 2009), thus exposing segments of former seascapes that are steeper than the fluvial graded profile (Schumm 1993; Holbrook 2001; Posamentier & Stepelman 2001; Holbrook et al. 2006). Sandy sediments mixed with shelf edge and slope collapses were transported to the basin floor through large incised canyons (Catuneanu 2006; Chen et al. 2014). In a lowstand system tract, the 'lowstand wedge' was developed during the early stage of base-level rise when the rate of rise is outpaced by the sedimentation rate (Catuneanu 2006). Therefore, the amount of sand supply and sand/mud ratio in deep water deposition was reduced by the base-level rise. However, the transgression/highstand system tracts generate a normal regression of shoreline far away from the shelf edge, which generally restricted the siliciclastic sediments on the shelf if there was not an abnormally high volume sediment supply. Hence, muddy depositional systems were developed in deep water where they lacked shelf edge feeding sources. However, with these recognized understandings, the relationship between sea level change and depositional processes are still debated. For example, upper slope sand which was transported by wind began to slump into deeper water and eventually be carried further into the basin by turbidity currents (Gardner 1992) or saline-density currents (Harms 1974). By contrast, (Loftin 1996) proposed that most of the sand accumulated during lowstands of sea level. The sandy sediments were "cannibalized" during transgressions and transported into the basin from the shelf margin that had been stabilized by a rising coastal water table.

Development of deep water deposition is controlled by multiple factors including basin tectonics, sea level fluctuations, and rate/type/source of sediment supply. The Delaware Basin which originated in the Proterozoic along the edge of the North American craton remained unusually stable with very mild tectonism throughout its history (Hills 1984). However, the Permian was a period of transitional sea level cyclicity between the high amplitude (60 to 100 m) (Crowley & Baum 1991; Soreghan & Giles 1999) and the low-amplitude (less than 10 m) (Goldhammer et al. 1990), which indicates that the Delaware Basin underwent a significant sea level change. The sediment supply in the Delaware basin is like a function of sea level change. Due to the stable, wide platform in this basin, the siliciclastics remained on the platform during the transgressive and highstand of sea level and were transported across the subaerially exposed shelf down to the deep water basin until the sea level fell (Saylor 2003). Therefore, at the stable carbonate shelf margin (active reef) without extensive and consistent clastic sediment supply, the role of sea level change becomes relatively prominent in the Delaware Basin. Hence, this paper mainly focuses on how sea level change influences the facies and architecture of deep water systems by controlling shelf edge processes. Combined with the global sea level change and relative sea level change in the Delaware Basin, this study mainly investigates the outcrops of the Bone Spring Formation and Delaware Mountain Group, as well as subsurface reservoirs in the East Ford and Red Tank fields in the northwestern Delaware Basin (Fig. 1). The architecture of the deep water systems evolved through time and space across the northern Delaware Basin slope under the influence of sea-level change has been documented. This paper aims to (1) reconstruct the depositional models of each deep water system by identifying sedimentary facies and architecture; (2) discuss the role of sea level change on cyclic sedimentation in deep water environments; and (3) reveal how sea level change indirectly controlled the deep water reservoir properties in the Delaware Basin.

Geological setting

The Delaware Basin is located in southeast New Mexico and northwest Texas with an area of over 26,000 km^2. The Guadalupe Mountain Shelf, Central Basin Platform and Diablo Platform were major sediment sources for this basin, all of which underwent uplift and erosion as part of the Ancestral Rocky Mountains deformational event (Hill Jr. 1981). However, the uplifts had become tectonically inactive and were onlapped by marine sediment by mid-late Permian times. The Delaware Basin was a deep water basin bounded by carbonate ramp and carbonate rim margins that developed on the western edge of the Central Basin Platform, the Northwest Shelf, and the Diablo Platform (Nance 2009). According to the reconstruction of the paleogeography of North America (Gradstein & Ogg 2004), the Delaware Basin was very close to the Pangaea continental margin. Thick evaporites/carbonates (like the San Andres Formation and Artesia Group) were deposited on the shelf and shelf margin, and mixed deposition of shelf derived siliciclastics of fine quartzose sandstones to coarse siltstones (Tinker 1998) and shelf margin derived detrital carbonates were developed on the slope and basin floor (Silver & Todd 1969). The source of the siliciclastic sediments was the Ancestral Rocky Mountains to the northwest of the Permian Basin (Mack et al. 2003). The observation of outcrops show that the carbonate-poor Brushy Canyon and Cherry Canyon tongues lap onto the low-angle lower San Andres and Grayburg ramp margins, whereas the carbonate-rich Cherry Canyon and Bell Canyon lap onto the higher angle forereef of the Goat Seep and Captian rimmed margins (Nance 2009). This probably indicates that a steepened carbonate margin facilitated carbonate deposition within the siliciclastics.

The Bone Spring Formation in the Delaware Basin is Early Permian (Leonardian) in age (Fig. 2), and is represented by outcrops of mixed siliciclastic/carbonate deposition. This interval in the subsurface is unconformably overlain by the Cutoff Formation, and conformably overlain by the Delaware Mountain Group. The Bone Spring Formation deposits are slope and basin floor equivalents to the Yeso and Victoria Peak Formation on the Northwest Shelf (Kerans et al. 2012). The Delaware Mountain Group (Middle Permian) comprises more than 1000 m of arkosic sandstone, siltstone and detrital limestone, which were deposited in deep water (Dutton et al. 2005). The Delaware Mountain Group on the slope and basin floor mainly consists of the Cutoff, Pipeline, Brushy Canyon, Cherry Canyon, and Bell Canyon Formations, which is equivalents to the San Andres Formation and Artesia Group (Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations) (Cohen et al. 2013) (Fig. 2). The shelf derived siliciclastics and shelf edge derived carbonate deposits in the Delaware Mountain. The group was deposited during intermittent sea level lowstands (Silver & Todd 1969; Meissner 1972). Basin subsidence outpaced sediment supply such that deep-water conditions were maintained until the close of the Guadalupian, after which Ochoan evaporites filled the basin and eventually blanketed the entire greater Permian Basin area (Nance 2009). Paleogeographical reconstruction shows that the relative sea level in the Delaware Basin was at a continuous lowstand (about 200 meters below present sea level) during the Late Permian stage (Kerans et al. 2012) (Fig. 2).

Data and methodology

Outcrop data including sedimentary logs, photo and hand samples of the Bone Spring, Cutoff, Brush Canyon, and Bell

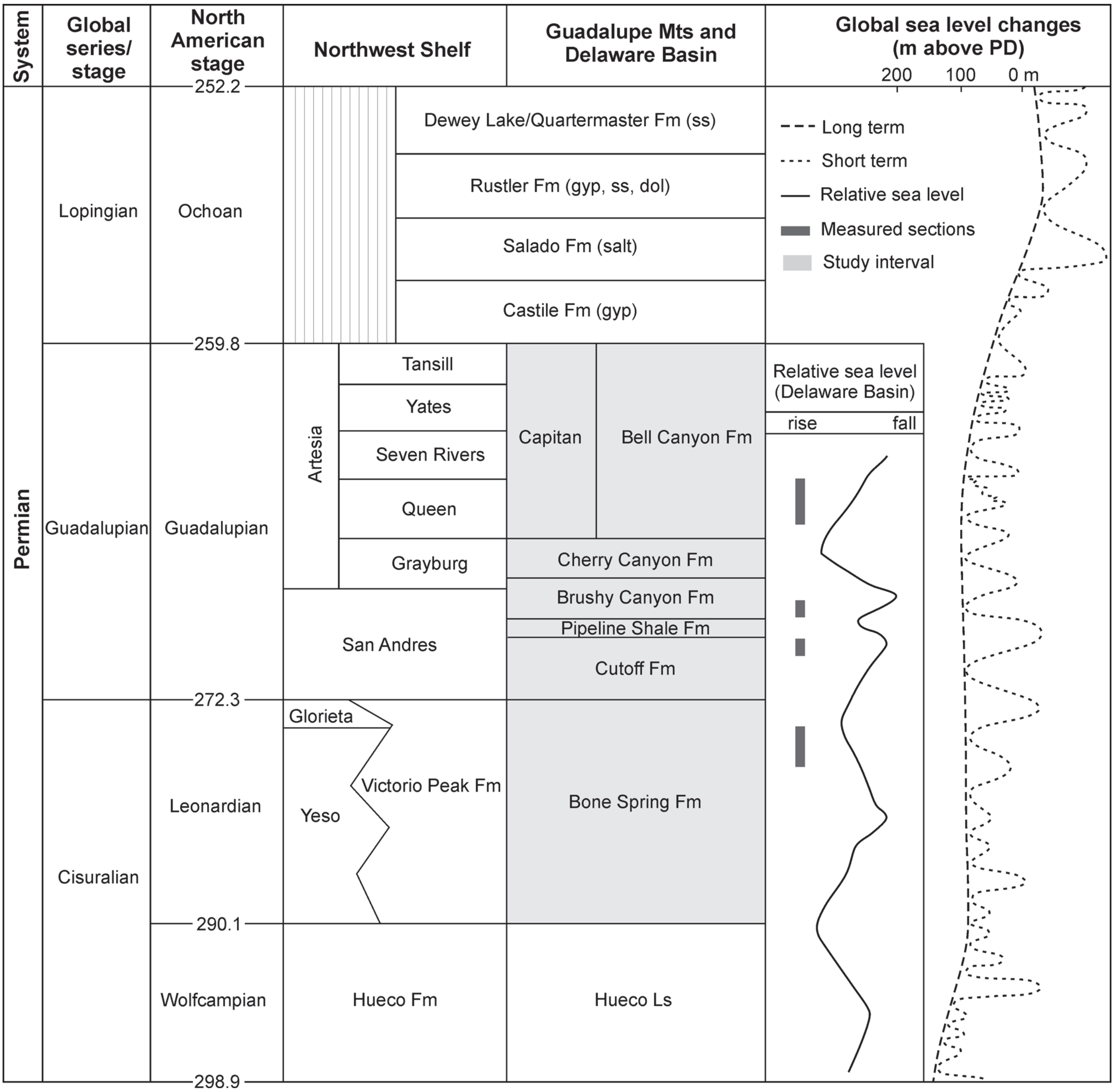

Fig. 2. Permian stratigraphic correlation chart with sea level changes in the Delaware Basin, west Texas. The stratigraphic chart was adapted from (Hawley 1983; Cohen et al. 2013). International Chronostratigraphic Chart; Global sea level changes are taken from (Haq & Schutter 2008); Relative sea level changes in the Delaware Basin come from (Montanez et al. 2007).

Canyon Formations have been collected from the northwestern Delaware Basin. The sedimentary logs are primary data in this study which are essential to identifying sedimentary facies and processes. Idealized Gamma Ray log curves were constructed by grain size and mineral components (Svendsen & Hartley 2001), which contribute to comparison with the characteristics of subsurface reservoirs. The global sea level change curve (Haq & Schutter 2008) and the relative sea level change curve in the Delaware Basin (Montanez et al. 2007) were combined with sedimentary logs, presenting the influence of sea level change on deep water deposition of each system tract. Subsurface wire-line logs of the equivalent intervals of the Bell Canyon and Brushy Canyon Formation in the East Ford field, and the Bone Spring Formation in the Red Tank field were correlated for characterizing reservoir architecture and properties of each system tract.

Based on the outcrop descriptions (a,b,c,d,e — in Fig. 1), sedimentary facies and processes were interpreted for each system tract and formation. Depositional models of deep water systems under different sea level stands were constructed to characterize the reservoir architecture. This paper summarizes the grain size, facies components, depositional regimes and net/gross ratio of falling-stage system tract, lowstand system tract, and transgressive/highstand system tract in outcrops. Finally, the influence of sea level change on deep water deposition and reservoir architecture is discussed with subsurface correlations of the Bell Canyon, Brushy Canyon, and Bone Spring Formations.

Facies associations

The Bone Spring Formation in the Lower Permian usually has lithology that includes muddy calciturbidites (mixed siliciclastic and carbonate) and limestone. The Delaware Mountain Group has lithology that predominantly includes fine to medium sandstone (with carbonate clasts), siltstone, limestone, conglomerates, and bentonites (volcanic ash) (Table 1). The carbonate clasts and conglomerates are mainly detrital carbonates derived from the lower San Andres/Victorio Peak ramp margin (Brushy Canyon), Grayburg ramp-margin (lower Cherry Canyon), Goat Seep (upper Cherry Canyon), and Capitan (Bell Canyon) rimmed shelf-margin complexes (Beaubouef et al. 1999; Kerans & Kempter 2002). On the basis of observation of the lithology of outcrops, four facies associations including mass-transport deposits, debris, turbidites, and hemi-pelagic to pelagic suspension were identified within the Bone Spring Formation and Delaware Mountain Group (Table 1) on the northwestern slope and basin floor of the Delaware Basin.

Mass-transport deposits

The Bell Canyon Formation includes mass-transport deposits found at road cuttings in the northern Delaware Basin (Fig. 1). The MTDs mainly consist of slumps and collapses of carbonate mega-breccias with sandy matrix (Fig. 3). The carbonate mega-breccias are commonly composed of rudstone clasts, dolomitized blocks, and skeletal packstones to grainstones. The diameter of mega-breccias and clasts ranges from 5 cm to 8 m (Fig. 3). Texturally, mega-breccias and clasts are characterized by poor sorting and irregular geometry. The MTDs also show blocky succession and sharp (erosive) contact with the underlying beds.

Mass-transport deposits (MTD) result from gravity-driven downslope movement of massive sediment particles where the main sediment support mechanism is non-fluid turbulence (thus excluding turbidity currents, fluidized flows, lique-

Table 1: Summary of facies associations and their lithology in the Bone Spring Formation and Delaware Mountain Group.

	Stratigraphy	Facies	Lithology
Delaware Mountain Group	Bell Canyon Fm	MTDs, debris, turbidites	Conglomerates, Rudstone blocks, Fine-grained sandstone
	Brushy Canyon Fm	Debris, turbidites (high density), slope mud	Medium sandstone, Fine-grained sandstone, Mudstone
	Cutoff Fm	Debris, turbidites (high density), pelagic deposits	Fine-grained sandstone, Mudstone, Bentonites
Bone Spring Fm		Debris, calciturbidites (low density)	Silty limestone, Fine-grained sandstone

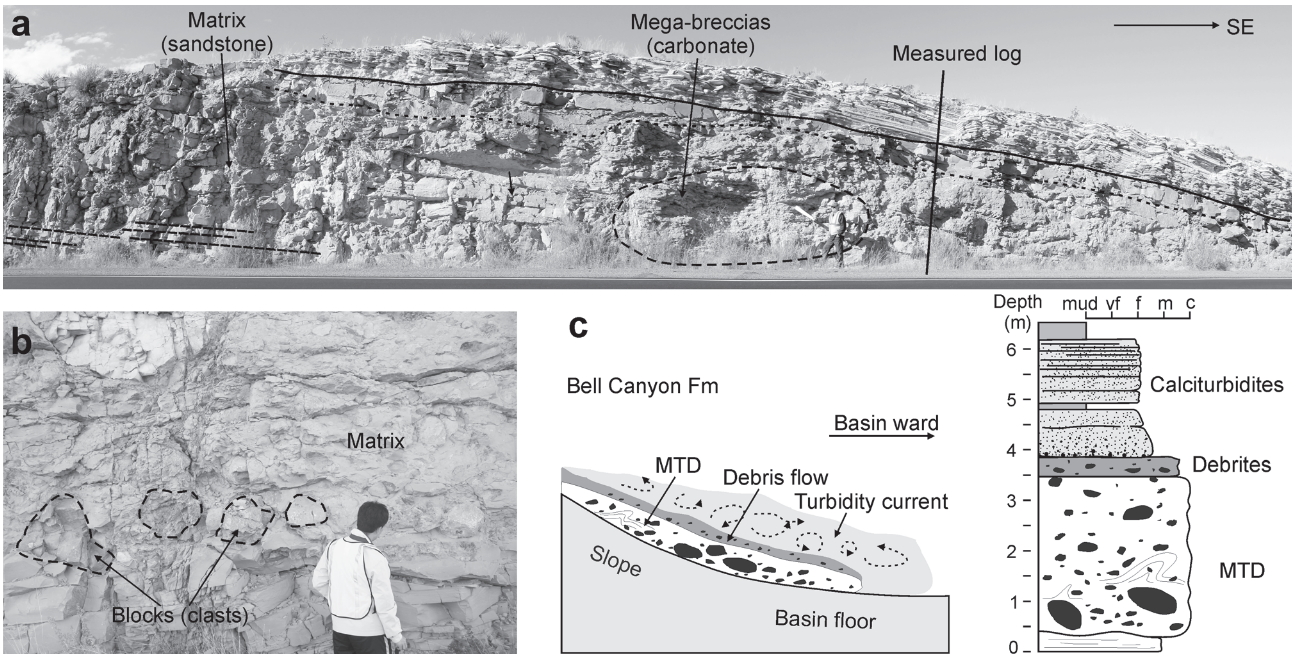

Fig. 3. Massive-transport complex consisting of slumps, debris, and turbidites in the Bell Canyon Formation (section e), Delaware Basin.

fied flows, and other non-cohesive, frictional flows) (Lowe 1979; Nardin 1979; Cook & Mullins 1983; Mulder & Alexander 2001; Posamentier & Martinsen 2011). This kind of deposition generally occurred as a result of decrease of accommodation due to rapid sea level fall, hydraulic degradation and over-steepening of the shelf margin, oversaturation of unconsolidated slope deposits, and winnowing of sediment by strong bottom currents (Wiggins & Harris 1985; Gawloski 1986; Saller et al. 1989). The Capitan Formation, equivalent to the Bell Canyon Formation, represents a shelf margin reef with a primary slope gradient of up to 30 degrees (Melim & Scholle 1995) which facilitates rock collapses. Reefs were exposed during the rapid sea level fall, and collapsed into blocks (Osleger 1998). These blocks fell down, and were transported massively with the sandy matrix down to the basin floor (Fig. 3). Due to the steep slope, the transport distance of these massive-transport deposits measured from the outcrop to the remnant reef was about 40 km (Fig. 1). Therefore, the MTDs in the Bell Canyon Formation were probably caused by over-steepening of the shelf edge and rapid sea level fall.

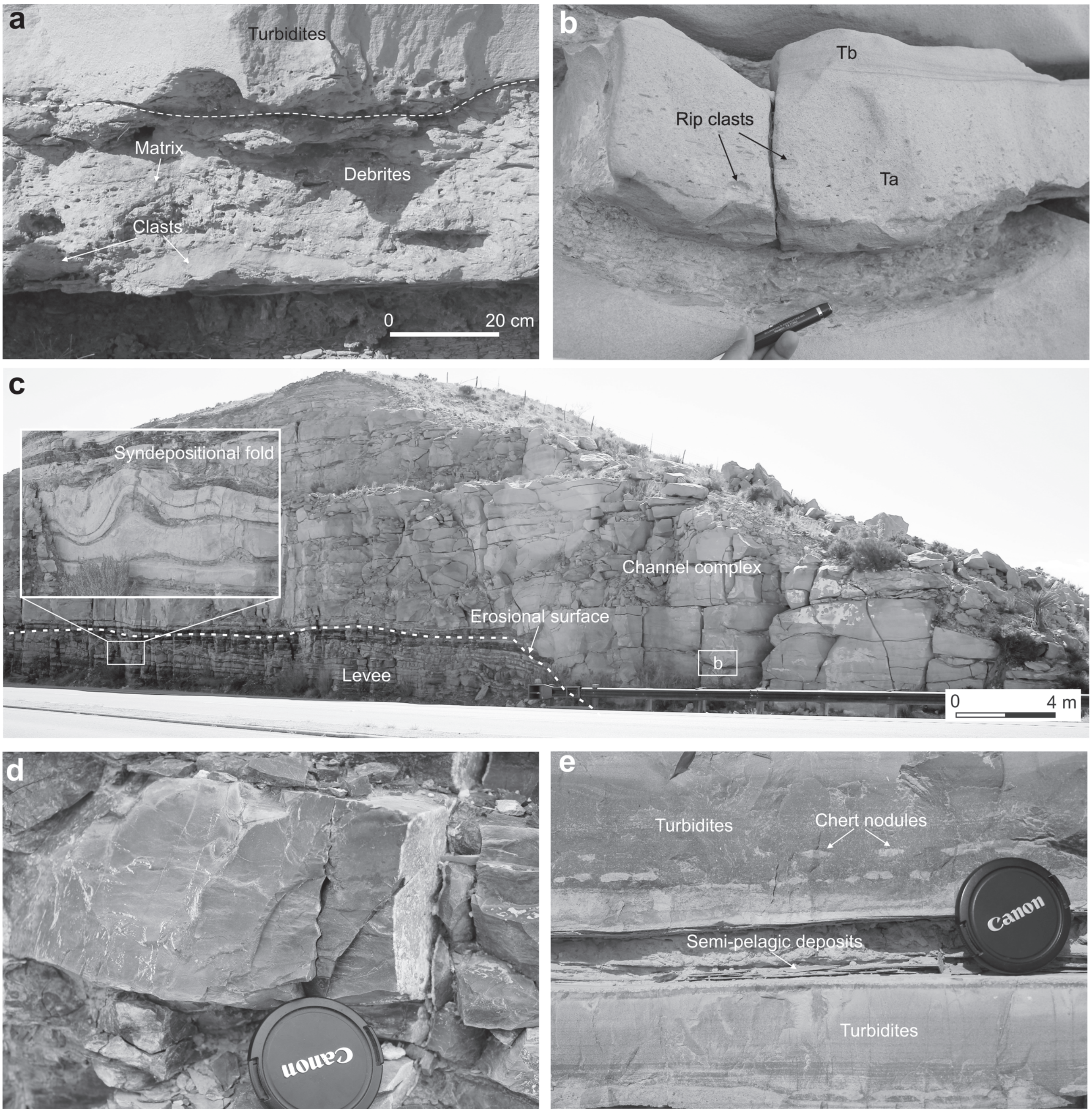

Fig. 4. Sedimentary facies of the deep water deposition in the northwest of the Delaware Basin. Note: **a** — debris deposits, Brushy Canyon Formation (section c), **b** — high density turbidites, Brushy Canyon Formation (section d), **c** — turbidity channel filled with stacked high density turbidites and syndepositional folds in levee (section d), **d** — low density turbidites (calciturbidites), Bone Spring Formation (section a), **e** — pelagic deposits, Cutoff (section b).

Debris flows

The debris in the Bone Spring and Brushy Canyon Formations was commonly associated with turbidites (Fig. 4a). The lithology types of debris range from lutite to boulder conglomerates. The conglomerate clasts are mainly composed of carbonate materials including algal boundstone, crystalline dolomites, quartz-rich sandstone, and even calciturbidites. The debris is characterized by massive bedding of matrix supported clasts showing irregular geometry (Fig. 4a). These deposits primarily show normal grading but occasionally inverse grading. The thickness of the debrites ranges from 0.5 m to 10 m. The beds generally exhibit sharp contacts with the beds above and below. Especially, the basal erosive surfaces indicate the incision capability of the debris flows.

The Bone Spring Formation and Delaware Mountain Group consist of large amounts of allochthonous debris deposits that were mainly derived from the shelf margin and slope of the Delaware Basin (Nance 2009). The reason for the combined facies association of debris and turbidites is the transport mechanism change during deposition. In the upper slope, the MTDs were motivated by shelf margin and slope failures including slides and slumps (Ruppel 2009). When these elastic or plastic mega-breccias/blocks were stopped by resistance and deceleration on the basin floor, their deposition was immediately followed by deposition from cohesive, clast-rich debris flows (Fig. 3). Turbidity currents continued further down onto the basin floor and deposited material later due to the finer grain size and lower sediment concentration.

Turbidites

High-density turbidity currents were defined by different criteria including current density and sediment concentration (sediment by weight and solids by volume) (Kuenen 1966; Lowe 1982; Shanmugam 1996; Posamentier & Martinsen 2011). The northwestern slope of the Delaware Basin exhibits plenty of amalgamated/isolated channels (Fig. 4b). There channels are filled by the high-density turbidites that primarily consist of high concentrations of sand sedimentation with slight to moderate grading. Erosive bases and rip clasts occur in the basal parts of the turbidite beds. The turbidity channels were commonly incised into the muddy slope or levee deposits where deformations like syndepositional folds were formed (Fig. 4c). The thickness of the channels ranges from meters to tens of meters. Shale is rare within these high-density turbidites, which are generally composed of partial Bouma sequences (Ta and Tb sections). Due to the high velocity, adequate sediment sources, and short hiatus between currents, upper sections (Tc and/or Td) of the turbidites were often truncated by later currents. The net to gross ratio of sandstone thickness to total formation thickness was calculated by outcrop measurements. The high-density turbidites generally filled channels on slopes and fan lobes on the basin floor with high net to gross ratios (55 %) (Fig. 4c).

Low-density turbidity currents consist of finer sediments including siltstone to very-fine sandstone. They might mix with carbonate materials forming calciturbidites (Bone Spring Formation), which appear as dark coloured, muddy thin beds with blocky or weakly normal grading (Fig. 4c). Slumps occur locally due to the soft deformations. Carbonate clasts with a diameter of a few centimeters occur at the base of the turbidity grade beds. Thickness of the calciturbidite beds ranges from centimeters to meters. These low-density turbidity currents travelled long distances (over 80 km), resulting in a wide extension in the deep water basin (Asmus & Grammer 2013). The calciturbidites in the Bone Spring Formation indicate active carbonate construction and less siliciclastic sediment coming from the shelf margin.

The Bone Spring, Cutoff, Brushy Canyon, and Bell Canyon Formations mainly consist of turbidites from high-density and low-density currents. The turbidite sandstone is generally composed of very-fine to fine quartz-rich sandstone, presenting partial/complete Bouma sequences. Turbidity currents were the primary transport mechanisms for sand sediments in the Bone Spring Formation and Delaware Mountain Group in the Delaware Basin (Zelt & Rossen 1995; Dutton et al. 2005), whereas suspension sedimentation may be an important mechanism for siltstone and clay deposition. The turbidites mainly compose channels, levees, overbank-splays, and fan lobes in the deep water area (Galloway & Hobday 1996; Gardner & Sonnenfeld 1996; Dutton 1999; Beaubouef & Friedmann 2000; Dutton et al. 2003; Vrbanac et al. 2010).

Hemi-pelagic to pelagic suspensions

The turbidites with partial Bouma sequences in the Cutoff and Brushy Canyon Formations are draped by massive or slightly laminated mudstone, which produces Bouma *Te* sections. The mudstone layers are usually very thin bedded, dark coloured and rich in organic material (Fig. 4d). Greenish, thin bedded bentonites were also developed between turbidite beds in the Brushy Canyon Formation. The muddy organic materials, interpreted as being largely hemi-pelagic, probably accumulated in deep water with reduced sand transport to the basin. According to major and trace element data identification, the bentonites were derived from a calc-alkaline series magma in a volcanic arc setting. The Las Delicias continental volcanic arc of northeastern Mexico is a potential source (Nicklen 2003). The volcanic ash from the southwest was deposited in deep water of the Delaware Basin from hemi-pelagic suspensions.

Sedimentary architecture of depositional systems

The successions of the Bone Spring Formation and Delaware Mountain Group are relatively proximal to the carbonate shelf margins where MTDs, debris, and turbidites developed within depositional systems that included mud-rich, sand-rich, and gravel/sand-rich deep water fans in the Delaware Basin. The different sedimentary facies which were developed by various transport mechanisms reflect the corresponding architecture and feeding systems (Pickering et al. 1986). The varying architecture within the depositional systems, which mainly consist of MTDs, channel-levee complex, submarine/basin floor fans, and supra-fans, was characterized by facies type, thickness, stacking patterns, and sand net-to-gross ratio in outcrops. Three depositional systems with different architecture, found in the Bone Spring, Cutoff, Brushy Canyon, and Bell Canyon Formations, are discussed below.

Muddy, elongate basin floor fans

The calciturbidites within the Bone Spring Formation are the muddiest successions in the Delaware Basin. The muddy intervals are characterized by dark colour, fine-grained, thin bedded, mixed siliciclastic/carbonate deposits. These stacked muddy beds show massive structure or a weakly fining upward trend (Fig. 5a). Rip clasts of carbonate fragments were developed locally within the muddy beds (Fig. 5b). Syn-depositional deformations were developed in the lower part of this formation (Fig. 5c). At the outcrop section a, the thickness distribution of these calciturbidite beds ranges from 0.1 m to 0.3 m (Fig. 5). The net-to-gross ratio of these calciturbidites is only about 26 %.

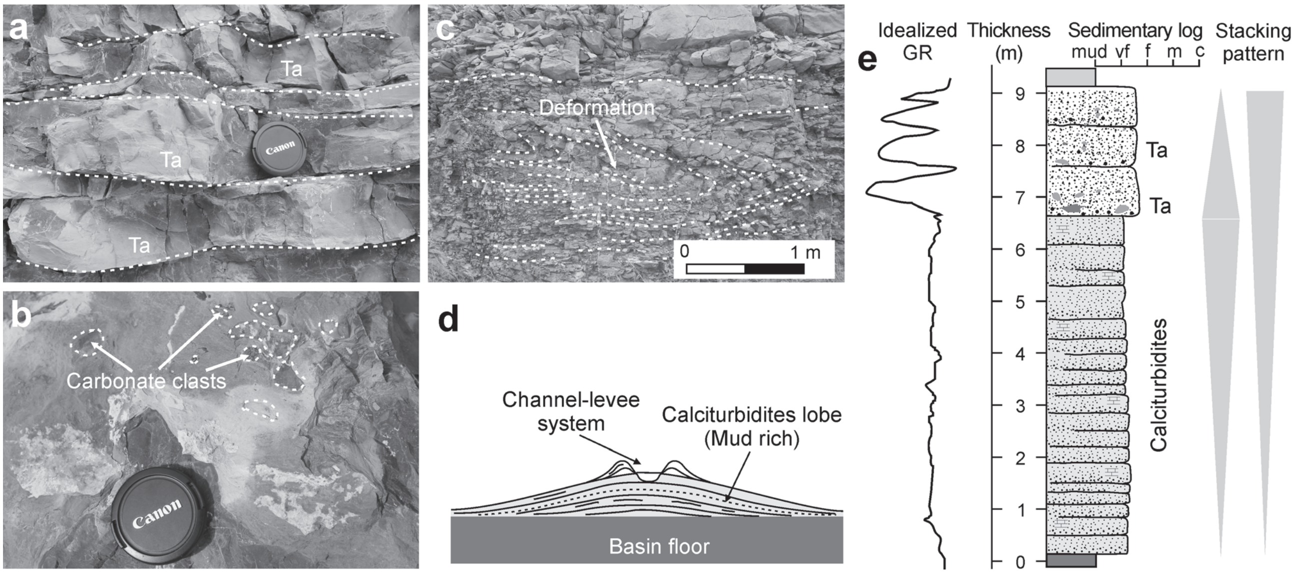

Fig. 5. Calciturbidite deposition from the mud-rich low-density turbidity currents during the transgression and high stand system tracts, Bone Spring Formation (section a).

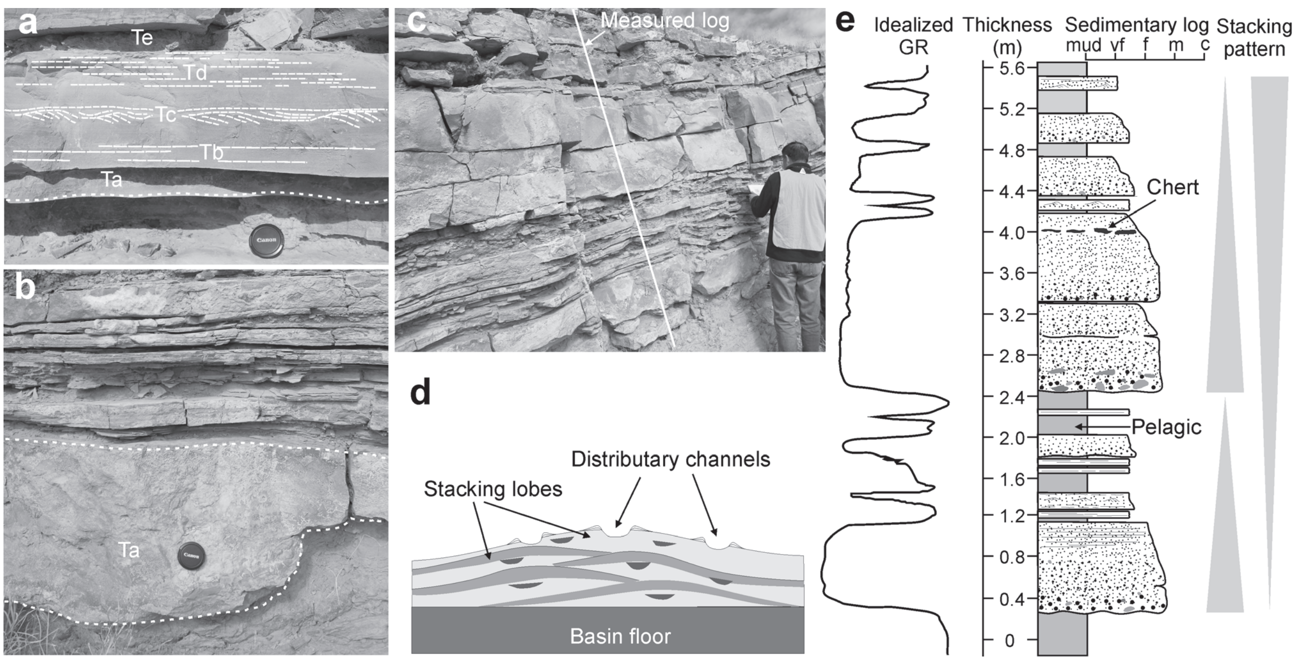

Fig. 6. Superfan deposition with sand-mud mixed and lobe-like submarine fan model of lowstand system tract, Cutoff Formation (section b).

The thin, graded beds lacking shallow water grains are interpreted as turbidity current deposits from the waning stage of debris flow sedimentation (Asmus & Grammer 2013), which indicate that the sandy intervals are commonly isolated within the muddy deposition. Due to lack of sandy sediment supply, the calciturbidites may construct elongated lobes on the basin floor (Reading & Richards 1994; Stow & Mayall 2000). The facies architecture from slope to basin floor is mainly composed of confined channel-levee systems, transitional systems, and unconfined sheety systems (Montgomery 1997). Within the muddy and elongated lobes, sandy layers have poor vertical connections but may have high horizontal connection in the sheety parts due to the low net-to-gross ratio.

Sand/mud interbedded, lobe-like deep water fans

In outcrops, the Cutoff Formation is characterized by high-density turbidity sandstones interbedded with dark coloured mudstone. The high-density turbidites locally show the full Bouma sequence (Ta, Tb, Tc, Td, and Te sections) (Fig. 6a). There are also sandbodies that only have grading beds (Ta) with irregular erosive bases (Fig. 6b). The thickness of the sandstone ranges from 0.3 m to 1.8 m. The muddy beds show thicknesses ranging from 1 cm to 20 cm. The sandstone layers show a fining upward trend in grain size. Overall, each interval between two erosive surfaces is thinning upward (Fig. 6e). The net-to-gross ratio of the stacked intervals is 57 %.

Commonly, these interbedded sandy turbidites and muddy Hemi-pelagic deposits generated lobe-like deep sea fans with supra-fans and distributary channels (Reading & Richards 1994). The full Bouma sequences indicate that each section of the material in the turbidity currents was deposited in sequence until all suspended matter had settled. The adequate time during episodes of the currents provided enough time for development of these typical turbidite successions. In the Cutoff Formation, due to the increased net-to-gross value, the sandbodies may have moderate vertical and horizontal connections. Although each single turbidite interval shows a fining upward trend, the amalgamated successions have thickening upward stacking patterns, which suggest lobe progradations of the deep water fans as well.

Sandy, amalgamated submarine fans

The Brushy Canyon Formation is characterized by amalgamated, coarse-grained high-density turbidites and debris (Fig. 7a). The Bell Canyon Formation mainly consists of large scale MTDs and debris (Fig. 3). The high-density turbidites primarily consist of the Ta, Tb, and Tc sections of the partial Bouma sequence (Fig. 7b). The thickness of the turbidite sets mainly ranges from 0.2 m to 1.5 m, locally up to 20 m (Fig. 4c). The debris which is comprised of matrix supported carbonate clasts generally occur at the base of turbidites. They commonly show thickness of 0.2 m to 0.5 m. Thin-bedded, hemi-pelagic deposits consisting of bentonites and laminated mudstone separate the turbidites and debris. The interval in outcrops has net-to-gross ratio up of 79 %.

The thick, amalgamated sandstone in the Brushy Canyon Formation formed channelized lobes on the slope toe and basin floor suggesting that large volumes of sandy sediments were accumulated with strong basal erosion. The Bell Canyon Formation, which is located close to the shelf margin

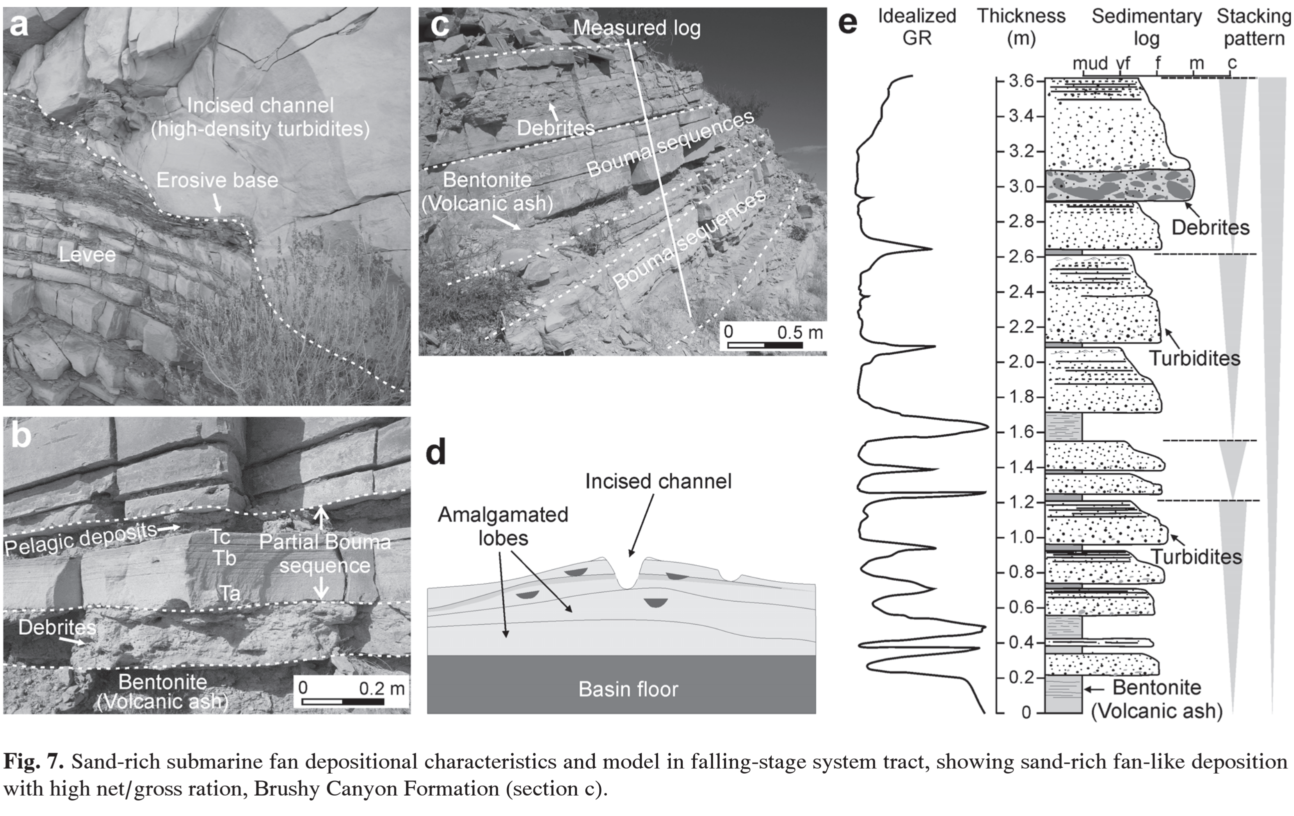

Fig. 7. Sand-rich submarine fan depositional characteristics and model in falling-stage system tract, showing sand-rich fan-like deposition with high net/gross ration, Brushy Canyon Formation (section c).

(section e — Fig. 1), comprises massive transport deposits on the steep slope providing sediments to the submarine fans on the basin floor. The MTDs, debris, and stacked high-density turbidites indicate sandy, amalgamated submarine fans deposited on the slope toe and basin floor. Therefore, due to the fast deposition, amalgamated turbidites with debris mainly settled on the slope toe and basin floor, forming stacked fan-like lobes (Reading & Richards 1994). The thin bedded muddy layers of hemi-pelagic deposits may provide interlayers for the underlying turbidite sandbodies. From the view of stacking patterns in vertical section, the stacked turbidites show thickening upward features, which may represent progradations of the submarine fans (Fig. 7c). The high sand net-to-gross ratio implies highly vertical and horizontal connections of sandbodies (King 1990). It may also indicate these submarine fan systems were fed by adequate sediment resources from the shelf margins.

Influence of sea level change on deep water deposition

As described above, the Bone Spring Formation and DMG in the Delaware Basin include alternating sandstone, siltstone, and mudstone on the slope and basin floor, and interbedding with carbonate-debris intervals along basin slopes. The character of the cyclicity and sedimentary patterns show that the architecture of the deep water deposition was strongly influenced by sea level change and position along the shelf-margin to basin floor profile. The sedimentary packages in this basin were subdivided into the falling-stage system tract, lowstand system tract, and transgressive/regressive system tract on the basis of sea level change. From the stratigraphic chart, the exposed outcrops in the Delaware Basin only show part of each formation and cycle of sea level change (Fig. 2). The Bone Spring Formation is mainly located at the transgressive and highstand states of relative sea level, the Cutoff Formation is approximately located at the lowstand of the relative sea level, while the Brushy Canyon and Bell Canyon formations are located at the falling-stage of the relative sea level. However, the order of stratigraphic units (from older to younger) does not match the order of system tracts in one sea level change cycle. In order to emphasize the influences of sea level change on the deep water systems, the system tracts within the sea level change cycle were discussed in this study by the following sequence order: falling-stage (the Brushy Canyon and Bell Canyon Formations), lowstand (the Cutoff Formation), and transgressive/highstand (the Bone Spring Formation).

Falling-stage system tract

During the falling-stage of the sea level, as the occurrence of forced regression, reef construction stopped, and the shelf margins were exposed widely. Fluvial incisions and bypass were caused by base level fall, which was lower below major topographic breaks (shelf edges). Under this circumstance, incised valleys which were characterized by V-shaped cross-sectional profiles and incised tributaries were the fairways for sediments transported into the basin. Due to the instability of the shelf edge topographic scarp, a significant amount of slides and slumps started to be triggered on the upper slopes. These mega-breccias and clasts with sandy or muddy matrix (MTDs) were transported down to the slope toe and basin floor. As the gravity flows developed toward the basin, debris flows consisting of allochthonous carbonate sediments

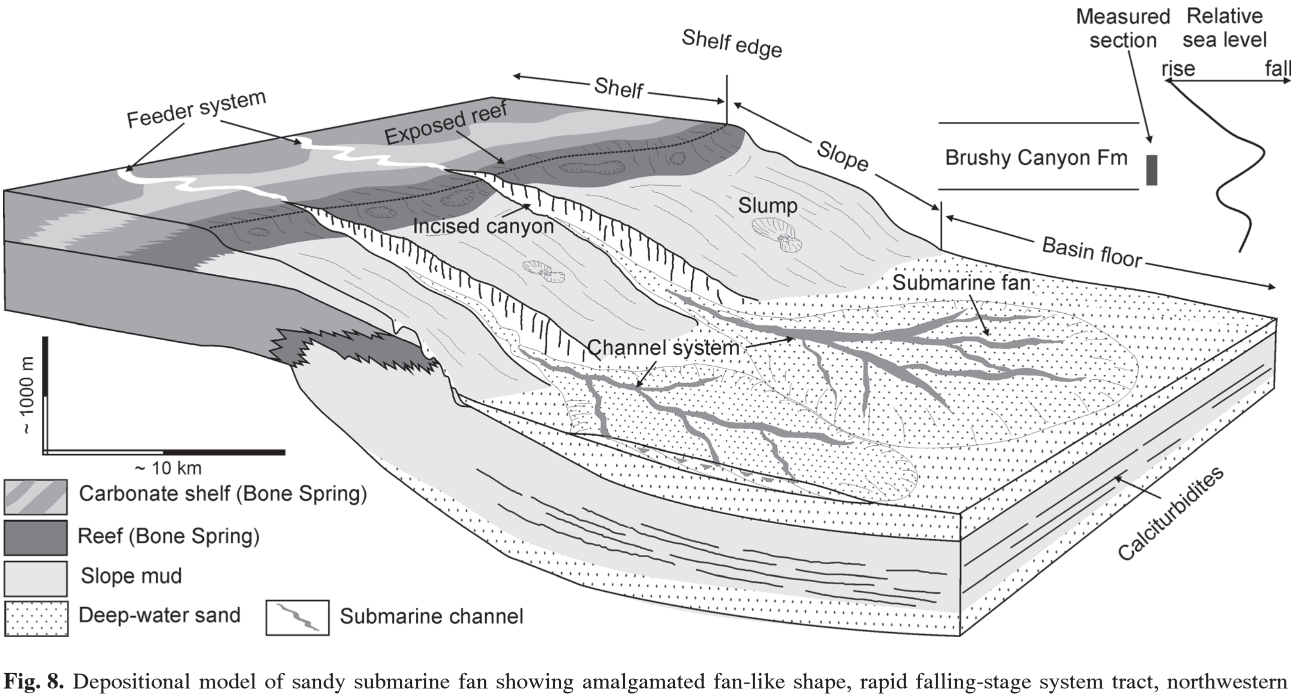

Fig. 8. Depositional model of sandy submarine fan showing amalgamated fan-like shape, rapid falling-stage system tract, northwestern Delaware basin.

derived from erosion of carbonate shelf edges accumulated in incised valleys on the basin slope.

The turbidity currents were commonly related to the debris flows which were further developed during the late period of falling-stage system tract. Generally, the turbidity currents in the deep basin are predominantly of high-density type due to the massive amount of sediment supply. Hence, the sandy turbidites making up submarine fans tend to be overloaded and aggradational (Fig. 8). Due to their high-density nature, the amalgamated sandy turbidites show high net-to-gross ratio of the initial sediment mixture. The insufficient amount of mud, which sustains the construction of levees, facilitated the deposition of unconfined splays relatively close to the slope toe (Fig. 8). Both the valley fills on the slope and the frontal splays on the basin floor are potentially sand-prone reservoirs.

Lowstand system tract

During the stage of early-rise of normal regression (Hunt & Tucker 1992), the shelf edge was still partly exposed. In this period, not only the net amount of sand supplied to the deep-water environment declines, but also the sand/mud ratio of the sediment load transported by turbidity currents. As a result, the lowstand sediments of the basin-floor submarine fan complexes were overall finer grained relative to the underlying late forced regressive deposits (Catuneanu 2006). In contrast to the MTDs and debris flows in the falling-stage system tract, the deep water deposition of the lowstand system tract is dominated by turbidites (high-density and low-density). The transition from high-density turbidites to low-density turbidites occurs along with the sea level rise (Nance 2009). Due to the relatively low sediment/water ratio, the turbidity currents tend to be underloaded on the slope, where channel entrenchment is often recorded.

As stability of the upper slope increased, pulses of turbidity deposition are common and show stacked lobes in the basin floor fans (Fig. 9). During lowstand of relative sea level, siliciclastic sediments prograde into the basin as channel-levees, splays, and lobe architectural elements of basin floor fan systems. The channel-levee-splay-lobe complexes primarily consist of sandstone-dominated intervals that alternate with generally widespread sheets of siltstone and mudstone. As sediment supply from the shelf margin slows, depositional axes of the basin floor fan starts to backstep onto the slopes during sea level rise. These successions indicate episodic deposition of sand and silt under waning current energy or episodes of density-driven sand deposition followed by relatively quiescent periods, when silt entered the basin either by wind or in hypopycnal plumes.

Transgressive/highstand system tracts

As the sea level rises, the trend of decrease with time in the amount of sand delivered to the deep water environment continues during the transgression and highstand periods. Therefore, this paper discusses the deposition of transgressive and highstand system tracts together. The thick, stacked, laterally confined shelf margin buildups (thickness up to 150 m) equivalent to the Bone Spring Formation indicate a dominance of vertical growth during this time, with only slight basinward progradation (Saller et al. 1989). As the accommodation increased, the reef started to reconstruct the shelf edge, which was drowned due to sea level rise. The development of shelf margin reefs over time efficiently attenuated sediment flux from shallow water. Eventually, the siliciclastic influx into the basin ceased, the clastic-free deposition mainly including low-density turbidites and hemi-pelagic deposition filled the basin to its rim.

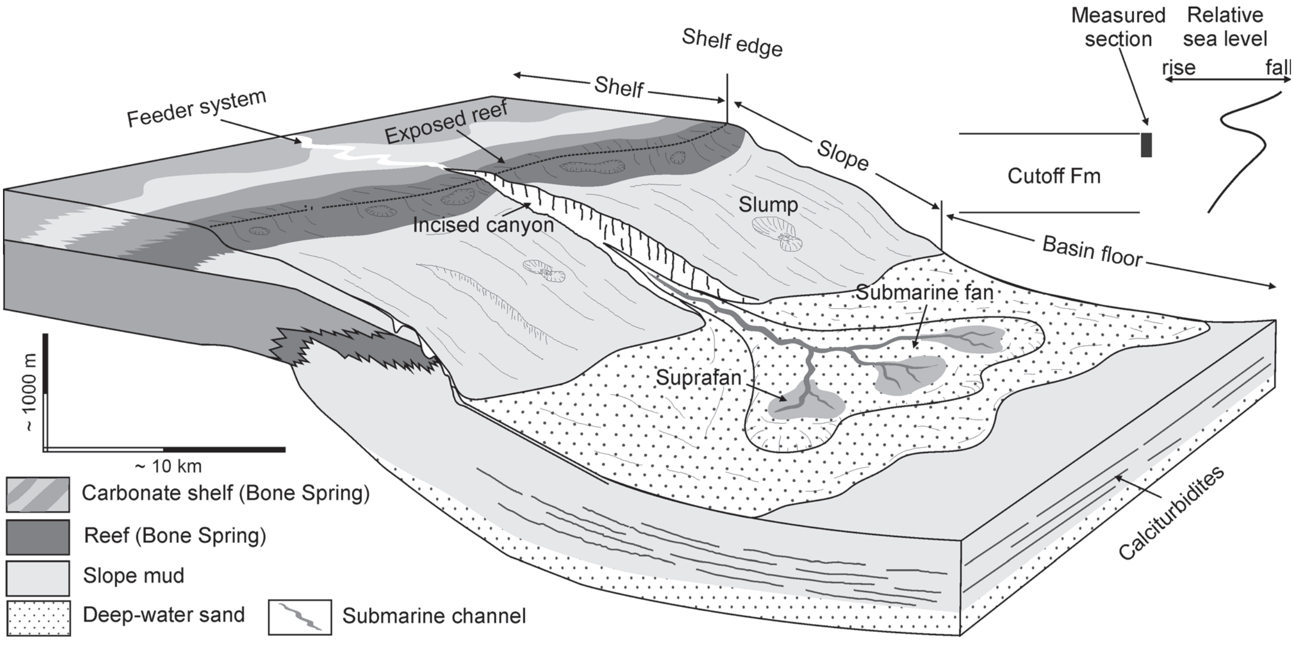

Fig. 9. Depositional model of the mixed submarine fans showing lobe-like shape with feeding system on shelf, the lowstand system tract, northwestern Delaware Basin.

During the transgressive stage, rapid shoreline transgression results in the stratigraphic profile showing overall retrogradational stacking patterns (Kerans et al. 2012). Due to the lack of sediment supply and rapid shoreline retreat, the upper slope is generally subject to no-deposition or a condensed zone that mainly presents hemi-pelagic deposits. Sediments were accumulated in shallow water and on the basin floor (Catuneanu 2006). However, low-density turbidity currents were still triggered by hydraulic instability and steep slope gradients. Because the higher proportion of mud sustains the construction of levees over a large distance, such low-density turbidity currents travel further than the high-density turbidity currents in the lowstand system tract. Therefore, the muddy deep water deposition with low-density turbidites commonly shows an elongated shape (Reading & Richards 1994) (Fig. 10). In the highstand system tract, active and continuous reef construction facilitates the aggradational steep shelf margin, also resulting in a paucity of gravity flows in the deep water. Nevertheless, debris flows were occasionally triggered by collapse from the oversteepening of reef rims. Mud flows without sandy sediment resources formed the low-density turbidity currents into the deep water environment of the basin (Fig. 10).

However, the turbidite sedimentation on the Mississippi Fan (Kolla & Perlmutter 1993), deep water fans in the Lance–Fox Hills–Lewis shelf margin (Carvajal & Steel 2006), and fans in the California borderland (Covault et al. 2007) show that large amounts of sand can be transported to deep water even during sea level rise and highstand. Point-sourced sandy fans may be well developed as a result of high sediment supply on the shelf during highstand, as opposed to sand/mud-rich deep sea fans which developed during falling or low sea level (Steel et al. 2008). For example, the Lance–Fox Hills–Lewis shelf margin in southern Wyoming suggests that high supply was critical in causing the accretion of this moderately wide Maastrichtian shelf margin, at a minimum rate of 47.8 km/My, and the generation of large, sand-rich fans during every shoreline regression across the shelf (Carvajal & Steel 2006).

Subsurface reservoir properties

A set of important reservoirs in the northern Delaware Basin, the Bone Spring Formation and DMG show the significant influences of sea level change on them at this carbonate shelf margin. Development of reservoirs depends on favourable facies, which is a result of the shifting of deep water sand accumulations related to sea level change. The sea level change controls the sediment sources, slope stability, and hydraulic regimes. Thereby, various sedimentary facies were formed in the deep water area by the sea level fluctuation. The primary control on reservoir distribution and architecture is the geometry of deep sea fan lobes in the context of slope and basin floor.

The Ramsey sandstone in the Bell Canyon Formation of the DMG in the East Ford Field shows thick, well lateral extension, and high net-to-gross ratio (62 %) of turbidity current sandstone (Fig. 11a). The amalgamated sandstone was interpreted as having been deposited in a channel-levee system with attached lobes and overbank splays (Dutton et al. 2003). From the trend of relative sea level change in the Delaware Basin (Fig. 2), this interval probably developed in the falling-stage and lowstand system tracts. The outcrops at basin margin present MTDs and debris during the falling-stage, while this subsurface sandstone on the further basin floor represent high-density turbidity deposits. The Ramsey sand-

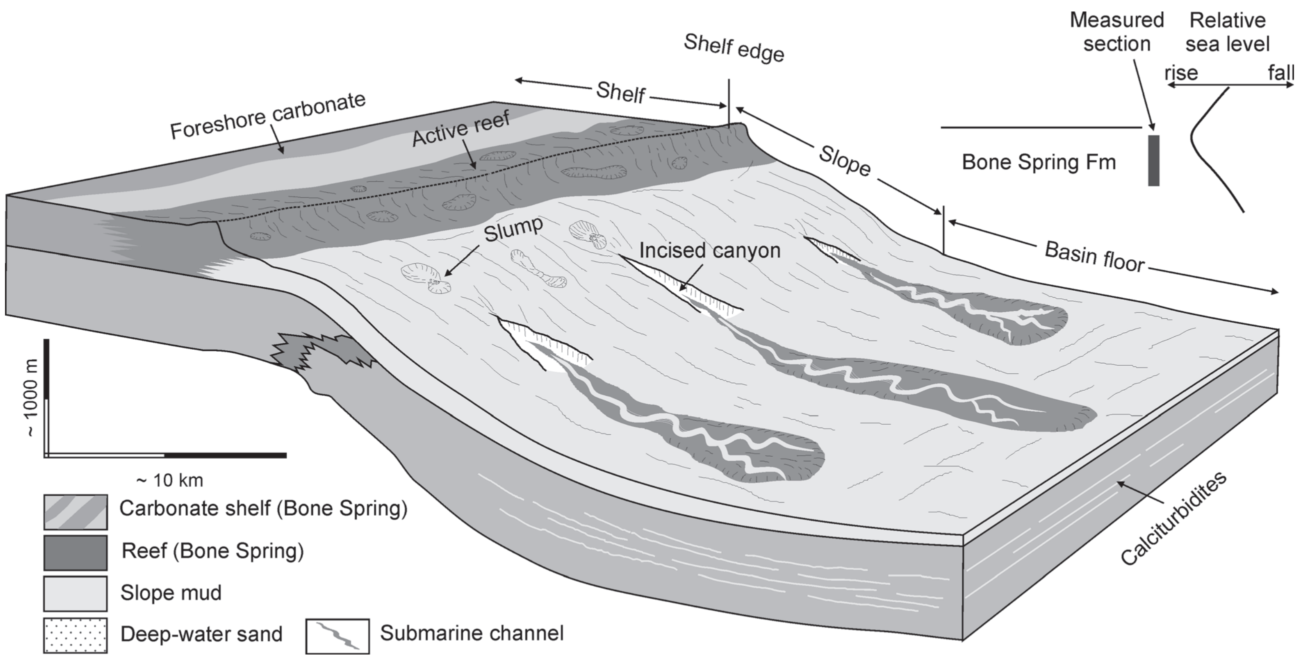

Fig. 10. Depositional model of the muddy submarine fans showing the elongated shape and non-feeding system on shelf, transgressive and highstand system tract, northwestern Delaware Basin.

stone has net-to-gross ratio greater than 60 %, even up to 93 % in outcrops (Table 2), which suggests high reservoir connections both in horizontal and vertical directions. Porosity in the Ramsey sandstones, which consist of well-sorted very fine grained arkoses, averages 22 % and ranges from 4.5 % to 30.6 %. The average sandstone permeability is 40 md (Dutton et al. 2003). Therefore, in the falling-stage system tracts, the slope and basin floor facilitate the develop-

Table 2: Net-to-gross ratios of sandstone in the deep water systems. Data were measured both from outcrops and subsurface reservoirs.

Sections \ Points		1	2	3	4	Average	Depositional systems
Outcrop	Section a	0.26	0.24	0.23	0.31	0.26	Muddy
	Section b	0.56	0.58	0.49	0.64	0.57	Interbedded
	Section c	0.72	0.68	0.69	0.77		
	Section d	0.76	0.73	0.82	0.93	0.79	Sandy, amalgamated
	Section e	0.86	0.84	0.87	0.82		
Subsurface reservoir	Bone Spring	0.19	0.44	0.33	0.24	0.30	Muddy
	Brushy Canyon	0.57	0.39	0.63	0.68	0.57	Interbedded
	Bell Canyon	0.62	0.62	0.60	0.64	0.62	Sandy, amalgamated

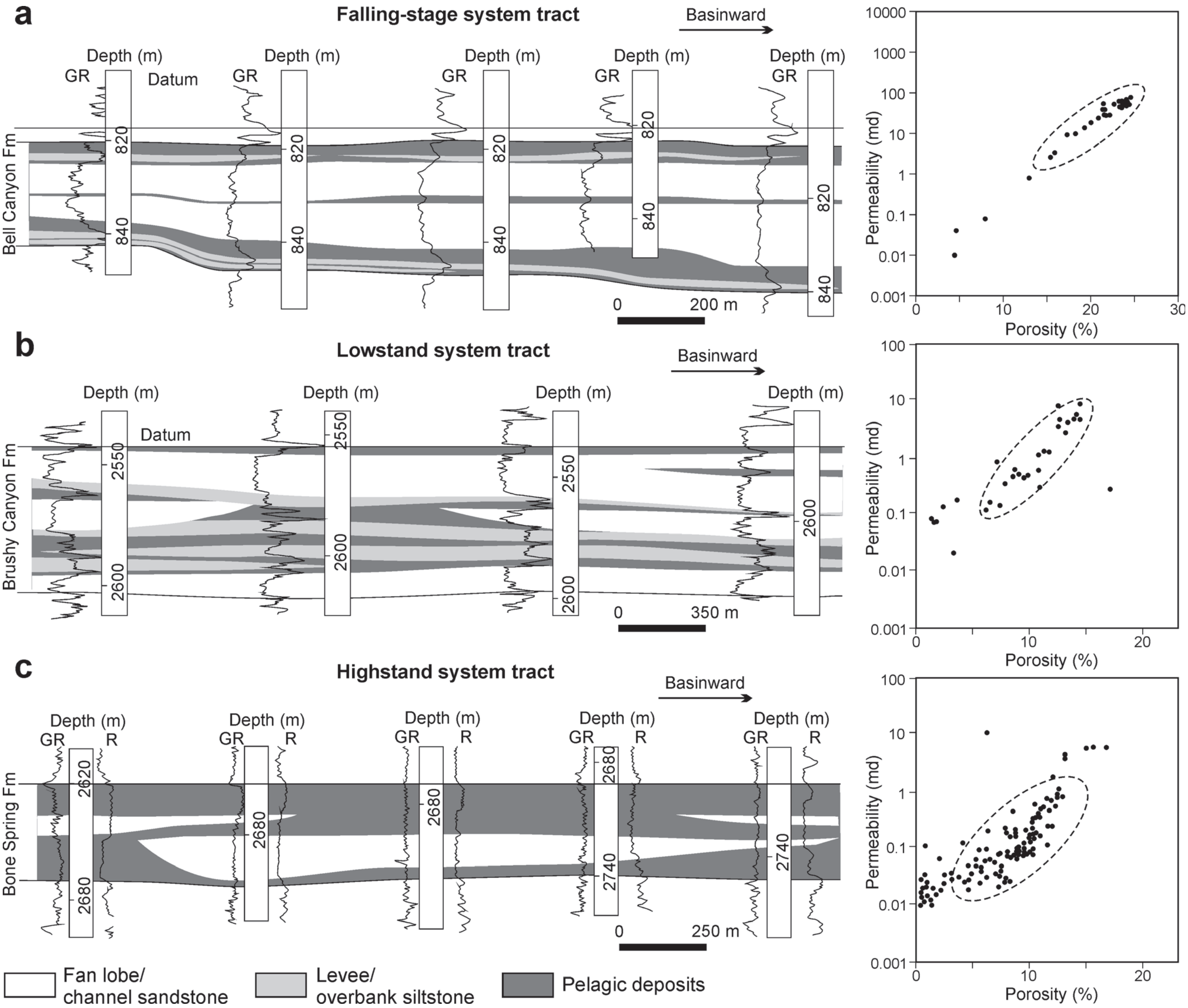

Fig. 11. Reservoir architecture and physical properties of deep water deposition in the Delaware Basin. Note: **a** — debris deposits in the falling-stage system tract, Bell Canyon Formation in the East Ford field (sandbody correlation was modified from Dutton 2008), **b** — high density turbidites sandstone in the lowstand system tract, Brushy Canyon Formation in the Red Tank Field (Green et al. 1996; Montgomery et al. 1999), **c** — low density turbidites in the transgressive/highstand system tracts, Bone Spring Formation in Red Tank field (Montgomery 1997).

ment of high quality sandstone reservoirs with well lateral extension and physical properties by debris flows and high-density turbidity currents. However, the MTDs and debris increased heterogeneity of the reservoirs due to the poorly-sorted carbonate clasts.

The sandstone reservoirs in the Brushy Canyon Formation (Red Tank Field) mainly contain well-sorted very fine sandstone interbedded with siltstone and organic rich micritic limestone (Green et al. 1996). As the sea level was lowstand during the Brushy Canyon period, this formation comprises a basinward thickening wedge of high turbidity deposits and overlies the Cutoff Formation. From the outcrop sections and subsurface correlations, the Brushy Formation presents medium net-to-gross ratio of 57 % and interbedded, well-connected sandstone architecture. The sandstones have an average porosity of 13.28 % and an average permeability of 4.33 md (Fig. 11b). The interbedded well-sorted sandstone and pelagic shale layers provide sets of reservoirs and seals.

The Bone Spring Formation in the Red Tank Field mainly consists of shale, siltstone, very fine sandstone, mixed sandstone/carbonate, dolomitized breccia, and limestone. These interbedded or mixed clastic/carbonate deposits were interpreted as muddy channel-levee, overbank, basinal limestone and pelagic shale (Montgomery 1997). Few debris flows were triggered by oversteepening reef or low amplitude sea level fluctuation. The relative sea level change curve in the Delaware Basin indicates that the Bone Spring deposition period was overall in the transgressive and highstand stages (Fig. 10). The sandy reservoirs of the Bone Spring Formation are commonly lenticular channels separated by muddy levee/overbank and pelagic deposits (Fig. 11c). This carbonate bearing interval has net-to-gross ratio of 30 % (Table 2), which suggests the isolated reservoirs have low connections between sandbodies. The sandstone reservoirs in the Bone Spring Formation are described as very fine grained, with porosity mainly ranging from 6.3 % to 16.5 %, and permeability from 0.1 md to 6.3 md. Hence, it shows much lower quality of reservoir properties than the DMG sandstone reservoirs. The reasons for this fact are discussed as follows. During the periods of transgression, rapidly rising sea level, shoreline retreat and carbonate construction at the shelf margin restricted the supply of clastic sediment into the basin, resulting in a muddy section from the slope to basin floor. In the highstand stage, vertical growth of the shelf margin increases the gradients of the reef escarpment. Combination of physical erosion (e.g. wave related) and collisions developed significant amounts of accumulating detritus with carbonate materials down to the basin floor.

Discussion

Sand sources

The Delaware Basin was situated close to the western margin of Pangaea during Guadalupian times and lay about 10° north of the paleo-equator of that time (Scotese & McKerrow 1990; Scotese & Langford 1995). The region consisted of a series of carbonate shelves and platforms (Kerans & Kempter 2002). It is well-known that sand resources like river-dominated deltas are not common on the active carbonate shelf. Hence, the source of the large volume of sandy deposits in the deep water of the Delaware Basin has been a subject of debate. The previous studies (Gardner 1996, 2003; Dutton 2003; Nance 2009) suggested that incised fluvial systems were developed on the flat shelf platform during lowstand of sea level. The very fine siliciclastics in the Delaware Mountain Group have also been interpreted as wind borne (Adams 1936; Fischer & Sarnthein 1988; Gardner 1992). The scarcity of clay in the Delaware Mountain Group is evidence to explain the aeolian link in the chain of transporting processes. There are also outcrops behind the reef presenting a thin layer of well-sorted, very fine grained sandstone with small aeolian ripples. Their grain size distribution features are in accordance with the deep water deposits (Dutton et al. 2003). The above facts may indicate that the sand dunes were delivered to the shelf margin and subsequently transported by turbidity currents into deep water during falling-stages and lowstands of sea level. On the basis of the incised channel systems and aeolian character of sandstone grain size, we believe that the large volumes of deep water sandstone originate from both incised fluvial systems and aeolian dunes developed behind the reef.

Comparisons of facies, architecture and reservoir properties

The characteristics of deep water depositional systems including sediment sources, architecture, and reservoir properties in the different system tracts are summarized on the basis of studies of outcrops and subsurface rocks of the Delaware Basin (Table 3). The sea level influenced the sediment flux which developed different deep water systems with various facies, internal and external features. Hence, the sandstone reservoirs within these systems show their impact on the hydrocarbon accumulation and production.

In the falling-stage system tract, the linear, sandy sediment resources derived from the shelf and exposed shelf edge consist of well-sorted, fine grained sands and megabreccias. Rapid sea level fall triggered MTDs, debris, and high-density turbidity currents on the steep basin slope, leading to the development of relatively small scale, coarse-grained deep water fans (Fig. 12). These fans with radial shape generally travelled short distances as a result of overload sediments and cohesive currents. The deep water deposits at this stage commonly show high net-to-gross ratio but low reservoir quality due to poorly-sorted, massive deposition. In the lowstand system tract, feeding systems from the shelf margin change to relatively fine and consistent mixed sandy and muddy sediments. The predominant hydraulic mechanisms are high- to low-density turbidity currents (Fig. 12), resulting in interbedded sandstone and mudstone. The moderate scale, lobe-like deep sea fans are developed on the slope toe and basin floor. These channelized lobes stack vertically and migrate laterally, forming high quality reservoirs with moderate net-to-gross ratio. Finally, in the transgressive and highstand system tracts, sandy sediments are trapped on the shelf by rapid sea level rise. Only muddy and carbonate deposits are developed in deep water areas. The low-density turbidity currents with carbonate materials form the primary

Table 3: Major sedimentary characters of deep water systems at different system tracts of sea level change.

System tracts	Falling-stage system tract	Lowstand system tract	Transgressive and highstand system tract
Size	Small (<5 km)	Moderate (5 km to 10 km)	Large (>10 km)
Shape	Radial	Lobate	Elongate
Slope gradient	High (>10°)	Moderate (5° to 10°)	Low (<5°)
Feeding system	Sandy	Sandy/muddy	Muddy
Supply mechanism	Mass-transport-complex, high density turbidity currents	Mainly high- and low density turbidity currents	Slumps and low- density turbidity currents
N/G	High (>60 %)	Moderate (30 % ~ 60 %)	Low (<30 %)

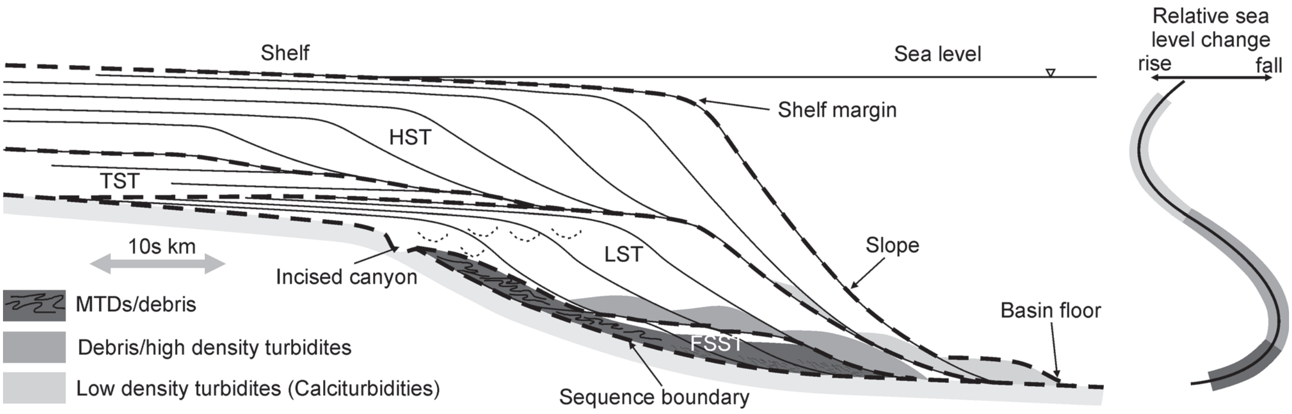

Fig. 12. Influence of sea level change on deep water deposition in system tracts (the system tracts model comes from Hunt & Tucker, 1992). The FSST (falling-stage system tracts) is dominated by MTDs and debris; the LST mainly consists of high density turbidites and debris; the TST and HST are composed of low density turbidites (calciturbidites).

facies of calciturbidites. Due to the suspension mechanism of feeding sediments, the muddy depositional lobes move large distance into the basin, forming the elongated deep water fans (Fig. 12). These muddy, sheety calciturbidites have low quality reservoir properties. Only the relatively sandy channel sandbodies are effective reservoirs. However, the overbank fills and pelagic shale are seal beds or even source rock for the underlying and overlying reservoirs.

Conclusions

The facies associations of the Bone Spring Formation and Delaware Mountain Group mainly consist of turbidites, massive-transport deposits, debris flows, and hemi-pelagic suspensions. These facies of sandstone with the carbonate materials compose the depositional systems of (1) sandy, amalgamated submarine fans, (2) sand/mud interbedded, lobe-like deep sea fans, and (3) muddy, elongated basin floor fans.

The deep water depositional systems which were proximal to the carbonate shelf margin were strongly influenced by sea level change. In the falling-stage system tract, the MTDs, debris, and high-density turbidity currents were triggered by rapid sea level fall and collapses of the exposed reef, leading to the development of amalgamated, coarse-grained, and radial deep water fans. In the lowstand system tract, the predominant hydraulic mechanisms are high- to low-density turbidity currents derived from the feeding systems of relatively fine and consistent mixed sandy and muddy sediments, forming the interbedded, fine-grained, and lobe-like deep water fans on the slope toe and basin floor. In the transgressive and highstand system tract, the low-density turbidity currents with carbonate materials developed the primary facies of calciturbidites. Due to the sandy sediments being trapped on the shelf by rapid sea level rise, the suspension sediments were transported large distances into the basin, resulting in muddy and elongated deep water fans.

The subsurface reservoirs also reflect the influences of sea level change on deep water deposition. The sandiest facies of MTDs and high-density turbidites deposited during the falling-stage system tract show relatively low reservoir quality due to the poorly-sorted, massive deposits. The well-sorted, fine-grained turbidites developed during the lowstand are the best reservoirs. They are characterized by moderate net-to-gross ratio, reservoir-seal sets, and favourable physical properties. The muddy calciturbidites, pelagic shale in the transgressive and highstand system tracts generally provide seals or source rocks, and minor reservoirs.

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