Thick turbidite successions from supply-dominated shelves during sea-level highstand

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ABSTRACT

Emphasis on the association between relative sea-level lowstand and the formation of sandy deep-water fans has tended to downplay the significance of high sediment supply and its potential to create deep-water fans, even during sea-level highstands. 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/m.y., and the generation of large, sand-rich fans during every shoreline regression across the shelf. It is surprising that fans developed from shelf-margin clinoforms that show systematically rising shelf-edge trajectories (proxy for rising relative sea level) as well as from those that show flat trajectories (stable to falling relative sea level). However, the latter, producing more sediment bypass, resulted in bigger and thicker fans, whereas the former produced somewhat smaller and thinner fans. We term the former highstand fans and suggest caution in using the lowstand model for high-supply systems.

Keywords: deep-water deposits, sediment supply, sea level, sequence stratigraphy.

INTRODUCTION

The growth of submarine fans, both modern (Flood and Piper, 1997) and ancient (Mutti, 1985; Posamentier and Vail, 1988), has been widely accepted as being preferentially associated with relative sea-level lowstand. In this model, fall of relative sea level below the shelf edge causes rivers both to reach the outer shelf and to entrench at the shelf edge (Johannessen and Steel, 2005), thus focusing the delivery of sand to deep-water areas. Conversely, this model postulates that during times of relative sea-level highstand much of the sand budget is stored on the shelf and coastal plain, and that deep-water fans become draped by muds (e.g., see Damuth et al., 1988). This model has been challenged using examples from narrow shelf settings (e.g., fans in the California Borderland, Gulf of Corinth, and Mediterranean Sea; see Piper and Normark, 2001; Ito and Masuda, 1988) or extremely high supply systems (e.g., Bengal Fan; Weber et al., 1997). In these cases slope canyons extending to almost the shoreline may receive sand from littoral drift or shelf currents during rising sea level. In addition, deltas may easily cross narrow shelves and provide sand for deep-water deposits under normal supply conditions during relative sea-level highstand. It has also been postulated that in moderately wide (tens of kilometers) to wide shelf (hundreds of kilometers) settings, significant volumes of sand can be bypassed to deep-water areas at highstand through shelf-edge deltas (Burgess and Hovius, 1998; Porębski and Steel, 2006). Nonetheless, documenting such delivery either in the modern or ancient has been difficult (except for suggestions from studies at the third-order time scale, e.g., McMillen and Winn, 1991), biasing researchers to interpret ancient deep-water deposits preferentially following the lowstand model. Thus, focus on this lowstand model has tended to cause us to overlook (1) the dominant role that sediment supply may play in deep-water sediment delivery, and (2) how such supply-dominated shelf margins can generate deep-water fans even during periods of rising relative sea level.

We provide here an example of how Maastrichtian deep-water fans of the Lewis Shale in southern Wyoming formed from shelf-edge deltas that we can document crossed moderately wide shelves in a high-supply setting. The submarine fans were generated by every one of at least 15 deltaic regressive shelf transits (Figs. 1 and 2), during a total time interval of less than 1.8 m.y., and there is evidence that many of these shelf transits happened while relative sea level was rising. Note that ‘‘rising’’ cannot be interpreted as late lowstand rising (Posamentier and Vail, 1988), but is highstand rising because it links back to a major shelf regression of the deltas.

GEOLOGIC SETTING AND DATA SET

Our data are from the Lance–Fox Hills–Lewis depositional system in southern Wyoming. This Maastrichtian succession is the final third-order shoreline regression of the Cretaceous Western Interior Seaway (Winn et al., 1987). The onset of the Laramide orogeny and associated tectonic subsidence resulted in rapid and significant southward shelf-margin progradation into the deep-water (as much as 430 m from undecompacted clinoform amplitudes) Washakie and Great Divide basins (Figs. 1 and 2). These basins formed a single asymmetric trough at that time, with higher rates of subsidence in the east. Correlation of ~500 well logs (with gamma ray, spontaneous potential, and conductivity curves) in this basin allows a three-dimensional tracking of individual fourth-order cycles through the linked fluvial to shelf to deep-marine depositional system of the Lance Formation, Fox Hills Sandstone, and Lewis Shale (Figs. 1 and 2).

In this system, the rivers of the Lance Formation (paralic and coal bearing, >200 m thick) and deltas of the Fox Hills Sandstone (mainly sandy river-wave deltas, >214 m thick) fed large volumes of sediment to deep-water areas of the Lewis Shale (>762 m). The high-supply character of the Fox Hills deltas allowed them to easily cross a moderately wide shelf (tens of kilometers), delivering large volumes of sand as slope and basin-floor turbidites.

DETERMINING CLINOTHEMS—UNITS OF SHELF-MARGIN ACCRETION

The term clinoform was introduced by Rich (1951) for the sloping segment of a shelf-margin profile. Here we use it for the entire surface connecting shoreline-shelf areas via deep-water slopes to basin-floor areas. Clinothems are thus the sand-prone lithosomes bounded by easily identifiable shale intervals (representing transgressions and maximum flooding surfaces; see Fig. 2) that in the Lewis–Fox Hills clinoforms penetrate landward up to 40–50 km. This distance, therefore, documents that the shelf was moderately wide. This is also the distance that the deltas/strandplains had to cross to reach the shelf edge during the subsequent regression. Clinothems (commonly with amplitudes of as much as 430 m) thus consist of (1) a regressive lower component produced by deltas and/or strandplains crossing the shelf, and in our data set always reaching the shelf edge; (2) a more steeply dipping basinward component created by sediment gravity flows on a long slope below the shelf edge, reflecting an increment of shelf-margin growth; and (3) a transgressive upper component produced by landward-migrating coastal plain, estuary, and barrier lagoon systems.

Clinothems in our data set are easily visualized by using a marked shale of basin-floor origin as stratigraphic datum (Fig. 2). This shale is of nearly basin-wide aerial extent, has high organic content and gamma-ray values

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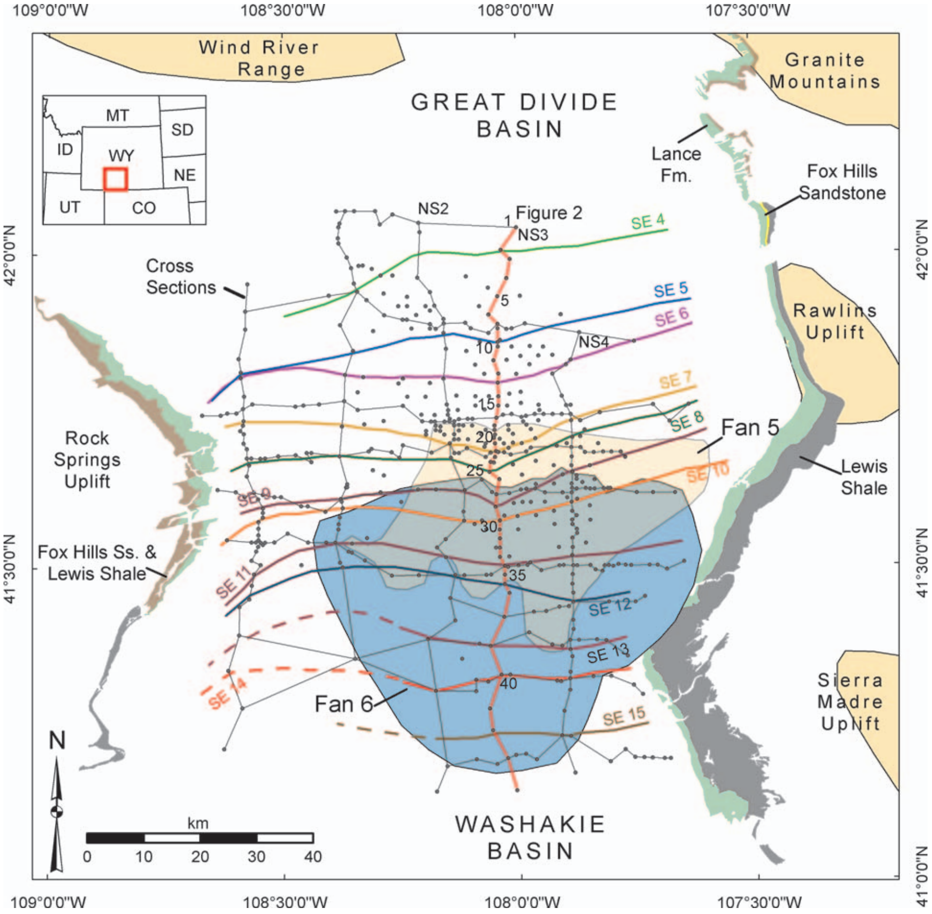

Figure 1. Location of study area (inset map), local geology (from Love and Christiansen, 1985), well database, shelf-edge positions (at time of maximum flooding during beginning of each cycle), and two basin-floor fans. Fan 5 was deposited during rising shelf-edge trajectory, whereas larger fan 6 was generated from flat shelf-edge trajectory.

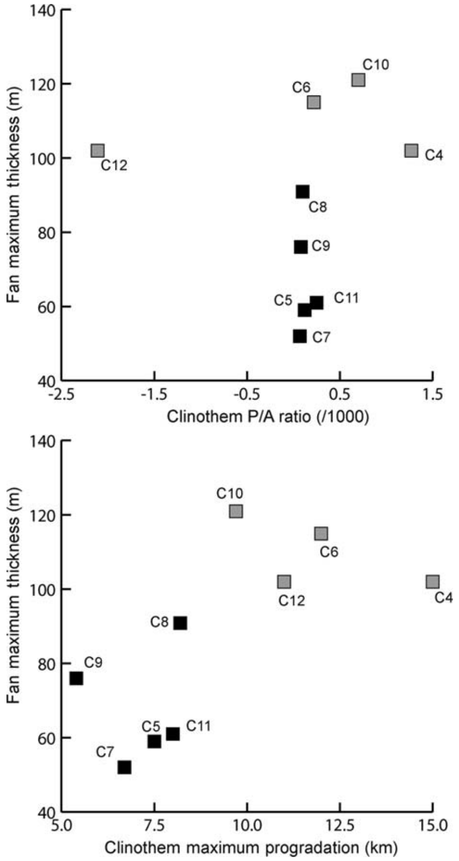

Figure 3. Maximum progradation distance and progradation/aggradation ratio (P/A) vs. maximum thickness for clinothems 4–12. Clinothems with flat shelf-edge trajectories (gray squares) tend to have higher P/A ratios and progradation distances, and thicker fans than clinothems with rising shelf-edge trajectory (black squares).

(Pyles and Slatt, 2000), and helps to tie well logs regionally. The shales bounding the clinothems have been correlated before (e.g., Asquith, 1970; Winn et al., 1987; McMillen and Winn, 1991; Ross et al., 1995; Pyles and Slatt, 2000), resulting in correlation schemes somewhat similar to ours and so increasing the confidence of the correctness of the correlation and quantification of key elements of the shelf-edge to deep-water system.

Such elements include the shelf-edge trajectory, fan thickness and area (where enough of the fan area is present), and the character and/or geometry of the sand accumulated on the slope. The shelf-edge trajectory (Steel and Olsen, 2002) represents the pathway of the shelf edge during the development of a given clinothem or group of clinothems (Fig. 2). We have quantified this trajectory by calculating the ratio between the average progradation and average aggradation of the shelf edge (Fig. 3) along cross sections NS2, NS3, and NS4 (Fig. 1), which cross most of the deep-water depocenters. Our measures are undecompacted, but our trajectory trends and relationship to deep-water fans seem to be similar to those that can be inferred from a decompacted published section in the area (Ross et al., 1995).

Figure 2. NS3 cross section (orange line with well number labels in Fig. 1) showing clinothems 1–16 from shelf to slope and to basin floor (great vertical exaggeration). Note that fan maximum thickness does not necessarily coincide with this cross section because fan depocenters shifted through time. Trajectory quantification was done using NS2, NS3, and NS4 cross sections.

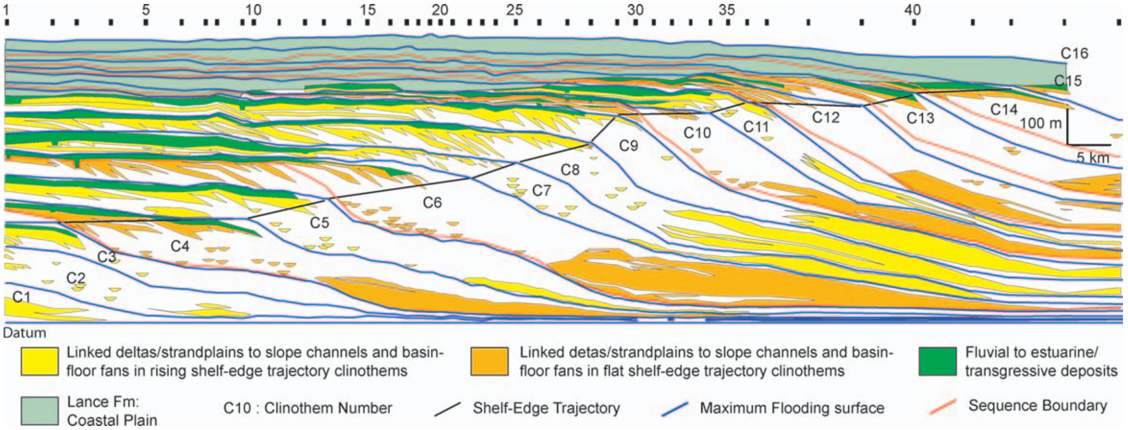

TABLE 1. RATES OF PROGRADATION AND AGGRADATION FOR DIFFERENT SHELF MARGINS*

Shelf margin	Age	Aggradation (m)	Progradation distance (km)	Time (my)	Aggradation rate (m/my)	Progradation rate (km/my)	Reference
Lewis–Fox Hills, Wyoming	Late Cretaceous	480<	86<	1.8	267	47.8	This work
West Siberia	Early Cretaceous	~1000	550	9.0	111	61.1	Pinous et al. 2001
Spitsbergen, Norway	Early Eocene	1125	34	6.0	188	5.7	Johannessen & Steel, 2005
Porcupine Basin, Offshore Ireland	Early Eocene	400	33	4.0–5.0	80–100	6.6–8.3	Johannessen & Steel, 2005
North Slope, Alaska	Early to Late Cretaceous	~1000	155	10.0	100	15.5	McMillen, 1991
Exmouth Plateau, Offshore Australia	Early Cretaceous	610	57<	6.0	102	9.5	Erskine & Vail, 1988
Pletmos Basin, Offshore S. Africa	Early Cretaceous	594	54	3.6	165	15.0	Brink et al., 1993
New Jersey	Middle Miocene	A few meters	31	1.8	Small	17.2	Steckler et al., 1999

*Progradation distance and aggradation measured in undecompacted cross sections (except for New Jersey). Errors may arise from cross-section orientations, lack of depth-converted seismic data, and limited aerial coverage (e.g., in the North Slope). Dating is reasonably good for all margins except for the North Slope whose time interval is poorly constrained. In the Lewis–Fox Hills margin, progradation distance is from shelf-edges 4–15 (Fig. 1) and time estimate is given by the Western Interior Seaway ammonites zones from *B. elliasi* (ca. 70.9) to the top of *B. clinolobatus* (ca. 69.1) (Winn et al., 1987; Kauffman et al., 1993).

FOX HILLS–LEWIS MARGIN AS A HIGH SEDIMENT-SUPPLY SYSTEM

Shelf-margin progradation and aggradation rates have been calculated for the Fox Hills–Lewis system and for a number of ancient shelf margins in which clinoform amplitudes are <1000 m (Table 1). The average progradation and aggradation rates for the Lewis shelf margin were 47.8 km/m.y. and 267 m/m.y., respectively. These are conservative estimates, as they do not consider the progradation and aggradation of the shelf margin prior to shelf edge 4 (Fig. 1; Table 1) because we do not have data on the early shelf-edge positions. Despite this, the Lewis margin aggradation and progradation rates are high compared to other margins, indicating that it was supply dominated.

LEWIS DEEP-WATER FANS

A main result of our analysis is that all the Lewis clinothems (for which we have enough basin floor and slope data) contain thick and aerially extensive deep-water fans. We have focused our analysis on clinothems 4 through 12 because in these cases we have access to nearly complete clinothems and can measure most of the variables described in the following. Fans in these clinothems are on the basin floor and toe of slope, although turbidite sandstones are also present on the upper slope. The fans (Figs. 1 and 2) form a southward- and eastward-migrating series of broad, lobe-like bodies. These sand-prone bodies have largely blocky to slightly serrate gamma-ray signatures, have maximum thicknesses between 52 and 121 m, and areas between 1387 and 2580 km^2. On the basin floor, they are rarely interbedded with shales (<3 m), but shale layers increase in number and thickness toward the toe-of-slope and fan-fringe areas (e.g., ~10 m).

SLOPE SANDSTONES

Slope sandstones, in contrast to basin-floor fans, are typically <12 m thick and may occur vertically stacked with intervening shale layers. Their log patterns tend to be blocky to serrate and spiky, and some have an upward-fining cap. Commonly these sandstones are laterally discontinuous or show drastic lateral thickness changes. We interpret the slope sandstone bodies as channel fills and inner levee deposits, in some cases forming multistory and multilateral channel belts. These channels acted as conduits through which sand was transported to the basin floor.

FAN DIMENSIONS AND SHELF-EDGE TRAJECTORY

In our data set, clinothems with either rising or with flattish shelf-edge trajectories partitioned significant volumes of sandstone into deep-water areas (Figs. 2 and 3). However, fan dimensions tend to be greater in those clinothems with flat to falling or very low angle trajectory, compared to the fans linked to rising shelf-edge trajectories. We define flat to falling or slightly rising shelf-edge growth trajectory by a progradation versus aggradation (P/A) average ratio of 0.22×10^3 -1.27×10^3, or negative values, and a maximum shelf-edge progradation distance of 10–15 km (clinothems 4, 6, 10, and 12). These clinothems contain fans with a maximum thickness from 102 to 121 m (average = 110 m) and an area from 2212 to 2580 km^2 (average 2359 km^2). In contrast, more steeply rising shelf-margin growth has a P/A ratio between 0.07×10^3 and 0.25×10^3 and maximum progradation distance of 5–8 km (clinothems 5, 7, 8, 9, and 11). In these clinothems, fan maximum thickness ranges from 52 to 91 m (average = 68 m) and fan area ranges from 1387 to 2234 km^2 (average = 1830 km^2). Thus, both flattish and rising shelf-margin growth produces fans, but there is a clear tendency for steeper shelf-margin accretion (and accompanying greater storage of the sediment budget on the shelf) to associate with smaller volumes of sand delivery into the deep-water slope and basin floor.

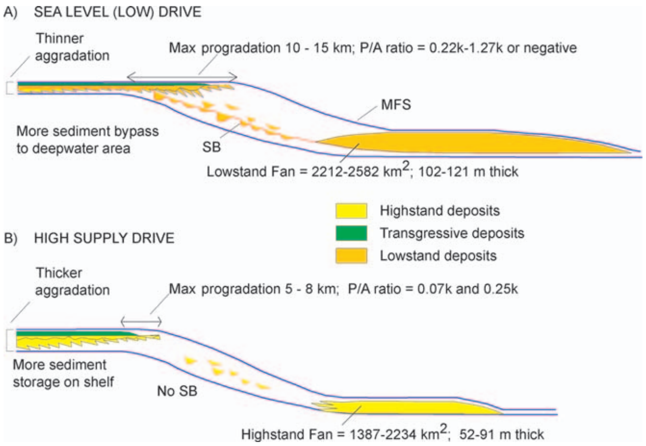

Figure 4. Schematic models for sand delivery to deep water. In A, fan is formed during relative sea-level fall (or still-stand), leading to generation of sequence boundary (SB), greater sediment bypass, thinner shelf aggradation, longer shelf-edge progradation, and thicker fan. In B, there is rise in relative sea level but fan is still formed due to high sediment supply. MFS—maximum flooding surface.

DISCUSSION: FANS DURING RISING RELATIVE SEA LEVEL

The shelf-edge trajectory, whether rising, flat, or falling, reflects the degree of aggradation or degradation at the shelf edge. This trajectory is largely controlled by the imbalance between the rate of relative sea-level change and the rate of sediment supply; a flat, highly prograding shelf-edge trajectory reflects stillstand to slightly falling relative sea level and implies that much of the sediment budget reaching the shoreline bypassed the shelf edge and was delivered into deep water. This scenario favors the generation of a sequence boundary and the deposition of thicker and more extensive deep-water fans, as happens in the Lewis clinothems (Figs. 3 and 4). Low accommodation therefore drives the progradation of the shelf margin and delivery of sand to deepwater areas.

However, fans are also present in all cases of rising shelf-edge trajectory (contrast with Johannessen and Steel, 2005), implying that they were generated when deltas arrived at the shelf edge even under conditions of rising relative sea level (and so without the generation of a sequence boundary), and even after significant sediment storage on the aggrading shelf. These fans, albeit smaller, still reflect significant delivery of sand into the deepwater areas. Such delivery supports the hypothesis by Burgess and Hovius (1998) (i.e., highstand fan generation); however, we stress that this scenario in moderately wide shelves is largely controlled by a high sediment supply, as suggested by Porębski and Steel (2006). The key role of a high sediment supply is that it is able to force the progradation of deltas and/or strandplains to the preexisting shelf edge despite rising relative sea level, and this is more easily achieved where shelf gradients are low and shelf currents do not rework much sediment along strike. Once deltas are at the shelf edge, then slumping, hyperpycnal flows, and other processes may cause turbidity currents and allow bypass of sand to deep-water areas (Piper and Normark, 2001). In this scenario, therefore, high supply drives the progradation of the shelf margin and delivery of sand to the slope and basin floor (Fig. 4).

Thus, it is likely that in cases of documented high sediment supply, the shelf-edge trajectory, rather than predicting the presence or absence of deep-water fans (Johannessen and Steel, 2005), would instead predict how voluminous these fans are. Flattish trajectories are linked to thicker and more extensive fans, whereas rising trajectories are linked to smaller fans (Fig. 4).

CONCLUSIONS

Thick and aerially extensive deep-water fans were formed in the Lewis Shale basin of southern Wyoming, regardless of whether the updip-linked Fox Hills shelf-edge trajectory shows a rising or falling tendency for any particular or group of delivery cycles. This indicates that submarine fans can develop either during sea-level lowstands (as conventionally predicted) or highstands. For the success of this scenario, the shelf delivery system needs to qualify as high supply, with typically high rates of shelf-edge accretion. In such high-supply shelf-margin systems, the deep-water fan volumes may be large even during highstand delivery, but fan volumes will become greater with the lowering of the shelf-edge trajectory and increase of the progradation distance, reflecting times of bypass of larger volumes of sediment to the basin floor.

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