CONDITIONS FOR COUPLING BETWEEN SHELF-EDGE ARCHITECTURE AND SUBMARINE-FAN GROWTH STYLE IN SUPPLY-DOMINATED MARGIN

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ABSTRACT

The linkage between relative sea-level change, shelf-edge architecture, and evolution of Maastrichtian basin-floor fans in Washakie Basin, Wyoming has been investigated at the scale of lobes, lobe complexes, and submarine fans using 630 wireline logs. The basin-floor fan deposits of two clinothems (9 and 10) form lobate shapes on the toe-of-slope and basin floor. At lobe
scale, amalgamated channels, channel-levees, unconfined lobe sheets and muddy deposits are recognized in the axis, fringe, and distal fringe of lobes respectively. The lobe complexes of the two clinothems are initially only weakly developed, indicating minor sediment volumes delivered to deep-water. Later, the lobe complexes of Clinothem 9 aggraded with fixed slope channels and without strong basinward or lateral migration and did so in concert with a highly aggradational shelf-edge during a period of interpreted relative sea-level rise. In contrast, the deep-water lobe complexes of Clinothem 10 prograded continuously for 20 km on the basin floor coeval with a flattish shelf-edge progradation and an interpreted slight sea-level fall. The depocenters of lobe complexes in Clinothem 10 switched laterally by compensational stacking and slope-channel avulsions. During the late development of both clinothems, the deep-water lobe complexes became smaller or retreated concurrent with shelf flooding. Washakie Basin deep-water fan-lobe complexes thus evolved through stages of initiation, aggradation, progradation, and retreat. The lobe complex growth stages of these deep-water depocenters were surprisingly well linked to coeval shelf-edge trajectory changes between successive, ca. 100 Ky maximum flooding events on the shelf. We suggest that the surprisingly close linkage of lobe-complex stacking pattern with shelf-edge behavior was because the Greenhouse Washakie Basin had a continuously, high, Laramide sediment discharge to the deep-water fans while the feeder deltas were at the shelf edge, despite significant sediment reworking of shelf-edge deltas by waves and tides.

INTRODUCTION

The lowstand of sea-level has been conventionally considered as the conducive condition of submarine fan deposition (Van Wagoner et al. 1987; Posamentier and Vail 1988). However, researchers argued conceptually (Burgess and Hovius 1998) and demonstrated with ancient
datasets that rising and high sea-level stand can also produce deep-water fans in high sediment-supply basins (Carvajal and Steel 2006; Covault et al. 2007; Kim et al. 2013) though the volume of lowstand submarine fans would be larger than that produced at highstand. The behavior and process regime of shelf-edge deltas (sediment feeder to deep water) in high sediment-supply basins is also now known to impact the presence and volume of deep-water fan-lobe complexes (Dixon et al. 2013). The stacking pattern of submarine fans has been reported from outcrop and subsurface data studies (Normark 1970; Mutti and Ricci Lucchi 1972; Walker and Mutti 1973; Mutti 1977; Posamentier and Kolla 2003; Hadler-Jacobsen et al. 2005; Deptuck et al. 2008; Prélat et al. 2009; Hodgson 2009; Mulder et al. 2010; Straub and Pyles 2012) and the progradation of channelized lobes accompanied by compensational stacking is generally accepted as the main builder of submarine fans (Piper and Normark 1983; Mutti and Normark 1987; Twichell et al. 1992; Gardner et al. 2003; Straub et al. 2009). The submarine fans developed in accommodation and sediment-supply dominated basins, however, growth style of fans remains to be improved. Progradational deltas at the shelf-edge are known to be a main supplier of sediment to deep-water turbidite lobes (Porębski and Steel 2003). We propose here that aggradation and progradation style of deltas at the shelf-edge is linked with the evolution and stacking pattern of deep-water lobe complexes. To test this hypothesis, the evolution of 27 deep-water lobe complexes at the toe of two basin scale clinothems are documented using 630 closely (500 m to 3 km) spaced wells from the high sediment-supply Maastrichtian Washakie Basin where shelf margins prograded at rates of up to 40 km/My (Carvajal and Steel 2006; Carvajal et al. 2009). We demonstrate a close relationship between the stacking pattern of the deep-water lobe complexes and the stacking pattern of the coeval shelf-margin depocenters (deltas).
GEOLOGY

Washakie Basin, one of the Laramide syn-tectonic basins, was formed between the Granite Mountains, Rawlins uplift, and Wind River Range during the early Maastrichtian (Steidtmann and Middleton 1991) (Fig. 1). Washakie Basin infill contains some 16 clinothems (C1 to C16), each of ca. 100 Ky duration, formed by the early Maastrichtian fluvial Lance Formation, shoreline/shelf Fox Hills Sandstone, and deep-water Lewis Shale (Carvajal and Steel 2006; Carvajal et al. 2009; Olariu et al. 2012). The undecompressed height of clinothems is between 230 m in the west and 430 m in the east due to the asymmetrical tilting of the basin. During a 1.8 My period, the shelf-margin prograded generally from north to south (west-east shelf-edge orientation) at a very high rate of >48 km/My and accumulated at rate of 267 m/My. The stratigraphy of the basin is divided into aggradational (C1 to C9) and progradational (C10 to C16) stages, based on the angle of the long-term shelf-edge trajectories (Carvajal et al. 2009).

DATA AND METHOD

A series of clinoform-bottomset intervals of submarine fan deposits, bounded by regionally traceable surfaces with high gamma-ray peaks, were defined within clinothems 9 and 10, using 630 wells in the southern part of the Washakie Basin over an area around 6,200 km² (Fig. 1). The deposits within each study interval represent a relatively short time period (ca. 20 Ky for 5 to 6 intervals within a 100 Ky clinothem; Olariu et al. 2012). Within each mapped bottomset interval, the sandy deposits represent fan-lobe complexes whereas mudstone or heterolithic strata represent fringe or abandonment stages. The plan-view distribution of lobe complexes is shown by sandstone thickness maps for each interval, with a 10 to 90 API gamma cut-off. To begin the correlation, the early lobe complexes at the foot of Clinothem 9 were picked in topographic low areas. Channels associated with lobe complexes are identified from capping blocky units of low
gamma-ray signal with a slight upward-fining pattern. Levees are recognized from repetition of thin beds interpreted from high gamma-ray serrated patterns. Unconfined lobe sheets were interpreted from repetition of units showing an upward-coarsening gamma-ray motif, and muddy beds from high gamma-ray signals within lobe complexes (Fig. 2).

RESULTS

Dimensions and Facies of Deep-Water Lobe Complexes

Lobate-elongate geometries can be recognized on sandstone isopach maps (Fig. 2A). The average size of a mapped lobe complex is about 28 km long, 15 km wide, and 21 m thick. The average ratio of length to width is 1.9, showing that lobe complexes are elongated in depositional dip-direction (N-S trend). The strike-oriented cross section shows a convex-up lobe complex that is thicker in the center and thins laterally to the west and east (Fig. 2B), whereas an asymmetric convex-up shape, with thicker proximal and thinner distal parts, is observed in the depositional dip-direction of lobe complexes (Fig. 2C). Amalgamated channels, channel-levees, unconfined lobe sheets and muddy deposits are recognized in the axis, fringe, and distal fringe of lobes respectively (Fig. 2D). The channelized lobe axes contain blocky gamma log pattern (amalgamated structureless or weakly flat-laminated sandstone beds with possible mud clasts and erosional surfaces), whereas the levees with more “erratic” log pattern are created by thin, ripple cross-laminated sandstone beds, interlayered with siltstone and mudstone. The lobate distribution of coarsening-upward bedsets below channel-levees is interpreted in terms of a progradational unconfined lobe sheets. Mudstone with siltstone laminae and some hybrid beds with soft sediment deformation are probably deposited in the distal fringes of lobes and generate an irregular log pattern with thin sandstone beds.

Stacking Patterns of Deep-Water Lobe Complexes
Two distinct stacking patterns have been observed in the fans of Clinothems 9 and 10. In the earliest stage of Clinothem 9, no sandy lobe complexes were developed, only mudstones (Fig. 3A). The first deep-water lobe complexes developed in the south-central and south-east parts of the basin and were connected northwards with slope-channel systems (Fig. 3B). The lobe complexes of Clinothem 9 aggraded strongly through time, over an area of around 1,100 km² within about 35 km from the toe of slope, but they did not prograde or switch laterally much (Fig. 3B-D). The lobe complexes of Clinothem 9 eventually became smaller, and insignificant in volume (Fig. 3E, F). During the early development of Clinothem 10, the deep-water lobe complexes in the south-east part of the basin prograded sub-longitudinally towards the south-west (Fig. 4A). However, during the further growth of Clinothem 10, the deep-water lobe complexes continued to prograde to the south and south-west for another 20 km, and aggraded about 100 m during the evolution of Clinothem 10 fan (Fig. 4B-D). Smaller lobe complexes developed in the western part of the basin and migrated south-eastward with little aggradation (Fig. 4B, D, E).

Linkage between Submarine Fan Architecture and Shelf-Edge Trajectory

The Fox Hills shelf-edge had been previously analyzed in term of its trajectory and depositional environments (Olariu et al. 2012) and it had been particularly noted that through the series of 16 clinothems, rising shelf-edge trajectories tended to produce smaller fans than those that were more strongly progradational (Carvajal and Steel 2006). This was because aggradation caused more of the total sediment budget to be stored on the shelf. We are now able to link the previous observations on the shelf-edge architecture with evolution of the lobe complexes within the basin-floor, deep-water fans. For Clinothem 9, the younger deltas developed on the inner shelf and were fluvial-dominated to tide-influenced deltas (Olariu et al. 2012) that did not fed
sediment to deep water (Fig. 3A). As the deltas approached the shelf edge after cross-shelf transit (mostly in the eastern part of the basin) more sediment was delivered to the shelf edge. The sediment became readily available to longshore currents that spread it along the shelf edge, eventually to be captured into the head of slope channels that funneled it to the deep water basin (Fig. 3B-D). During a late of clinothem growth the sea level was slowly rising as suggested by the smaller aggradation rates, and as a consequence thinner deltas developed at the shelf edge and smaller or no fans developed in the basin (Fig. 3E, F). The absence of significant deep water fans in the west can be explained by the fact that distributaries were few or small there, and most of the sandstone was concentrated in narrow elongate belts by eastwards longshore drift along the western shelf margin (Olariu et al. 2012) (Fig. 3G). The main sediment feeder for the deep-water lobes of Clinothem 9 were the shelf-edge deltas sited close to the slope channel heads on the upper slope, though wave-generated longshore drift of sand belts from the west also played an important supply role (Carvajal and Steel 2009). The minimal lateral migration of the Clinoform 9 fan lobes is likely to have been caused by relatively fixed feeder channel systems at the shelf edge and on the slope. The dominantly aggradational pattern of the deep-water lobes of Clinothem 9 is interpreted as a response to the coeval shelf-edge aggradation rate of 50 m/100 Ky (Fig. 3H).

For Clinothem 10, the earliest deltas arrived at the shelf edge quickly, probably during highstand and were highly progradational suggesting significant sediment supply (Olariu et al. 2012). They almost reached the shelf edge in the eastern side of the basin providing sand to the deep water fans (Fig. 4A). The following cycles were mostly progradational and formed shelf edge deltas continually (Fig. 4B-D). High sediment flux and a relative sea-level fall are interpreted to have been responsible for the marked progradation of the shelf-edge deltas with thin topsets (Fig. 4G)
(Carvajal and Steel 2009) and, in contrast to Clinothem 9, for the strongly prograding deep-water lobe complexes of Clinothem 10 in the southeast areas of the basin (Fig. 4B-D, F). The deep water lobe complexes migrated gradually to the west, probably as a result of the migration of the feeder channels and/or the compensational stacking processes related with topography. The lobe complexes in the south central and southwest of basin probably delivered from smaller river systems on the shelf or by the sporadic supply of longshore-drifted sediments along the southwestern shelf-edge (Fig. 4B, D, E).

**DISCUSSION**

_Evolution of Submarine Fans in Accommodation-Dominated vs Sediment-Supply Dominated Margins_

The general initiation-growth-retreat evolution of submarine fans (e.g., Hadler-Jacobsen et al. 2005) is probably widely applicable. The style of submarine fan growth, however, is likely distinctive, and driven by grain size, type of feeder system (Reading and Richards 1994), relative sea-level behaviour (Van Wagoner et al. 1987; Posamentier and Vail 1988), and sediment-supply rate (Carvajal and Steel 2006, 2009). As noted above, there is growing agreement that the two end member models for margin growth are (1) the conventional accommodation-dominated model (Exxon Model) whereby delivery of sediment to the shelf edge and to the basin floor is driven by sea-level fall and reduced accommodation (Fig. 5A) (Van Wagoner et al. 1987; Posamentier and Vail 1988; Kolla 1993), and (2) a sediment-supply dominated model whereby sediment is delivered to the shelf edge and to the basin floor primarily by high sediment flux, irrespective of sea-level fall or rise (Fig. 5B) (Carvajal et al. 2009).

In the *accommodation-dominated model* above, sediment is supplied to submarine fans from the combination of normal fluvial erosion and delivery across the shelf and local erosion from
valleys incised on the shelf, all of which is routed into deep-water during relative sea-level fall, even from modest-size rivers (Fig. 5Aa). During sea-level fall the shelf-edge progrades, but can be significantly eroded at times and sediments are likely delivered to deep water via slope channels and eventually, resulting in early-stage progradation of submarine fans. During sea-level rise, the shelf edge deltas and the basin floor fan would be disconnected, but the deepwater slope would have continued to prograde, but with muddy fans and slumps and eventually a muddy prograding complex as sea level came back above the shelf edge (late lowstand wedge of Posamentier et al. 1991) prior to transgression back across the shelf. During shelf transgression fluvial channels and incised valleys on the shelf become widened and eventually filled (Heller et al. 2001; Strong and Paola 2008). At this late stage, sediments are trapped mainly on the shelf and submarine fans receive little and/or no coarse grained (sand) sediment (Fig. 5Ab).

For the supply-dominated margin model (Fig. 5B), in contrast, high sediment flux allows deltas to transit the shelf, bypass onto the slope and form submarine fans at any sea-level stand (Covault et al. 2007). Unlike the conventional model, fan building here tends to continue during both fall (Fig. 5Ba) and rise (Fig. 5Bb) half cycles, but there can be additional influence of this rise and fall despite the high supply. During relative sea-level fall, sediment eroded from the shelf (restricted amount due to high sediment flux) and sediment bypassed through rivers build large submarine fans in deep-water. The progradation of submarine fans which are spatially extensive across shelf edge will be greater than that of localized fans connected with relatively fixed slope channels in accommodation-dominated settings, if sea-level fall rates are the same in both cases. However, what is different for high sediment-supply systems is that the shelf-edge will prograde despite relative sea-level rise (Carvajal and Steel 2006) and slope channels consistently connect shelf edge deltas with basin floor (Fig. 5Bb).
The present data, both the calculation of sediment discharge and clinoform progradation rate (Carvajal and Steel, 2012), from clinothems 9 and 10 in Washakie Basin show that the system can be classified as high sediment supply compared to other margin systems. It is therefore of some interest to look at the differences between clinothems 9 and 10 within this high sediment flux setting. In Clinothem 10 we note that marked progradation of the shelf-edge caused a corresponding progradation of the genetically related submarine fan system, even during modest sea-level rise, as shown by the shelf-edge trajectory (Figs. 4, 5Ba). Further, in cases where the rate of relative sea-level rise became high, the shelf-edge aggraded (rising and prograding trajectory) and also resulted in dominantly aggradational submarine fans as seen in Clinothem 9 (Figs. 3, 5Bb). Toward the end of the aggradation stage the submarine fans retreated concurrently with the autogenic or allogenic retreat of the shelf-edge (Kim and Muto 2007; Muto et al. 2007). Clinothems 9 and 10 of Washakie Basin thus demonstrate that the shelf-edge trajectory of a sediment-supply dominated margin can be significantly influenced by sea-level rise, and that this influence affected both shelf-edge trajectory and basin-floor fan behavior (staking pattern). This resulted in a supply-dominated but accommodation-influenced setting whereby an aggrading shelf-edge trajectory with coeval aggrading deep-water fan lobes changed to become a strongly prograding shelf-edge with coevally prograding fan-lobe complexes (Fig. 5B). To summarize the conditions for mirroring aggradation-progradation pattern between shelf-edge deltas and deep-water fans in high supply Washakie margin: (1) Clinothem 9 maintained the flux to the shelf-edge even during the relative sea-level rise and aggraded fans by sediments funneled through stable slope channels; (2) Clinothem 10 had high enough sediment supply for spatially extensive progradation across the shelf edge even during the relative sea-level fall concurrent with strong fan progradation.
CONCLUSIONS

Deep-water fan-lobe complexes of the high-supply Washakie Basin evolved through stages of initiation, progradation, aggradation, and retreat. These stages of evolution are widely seen in staking of deep-water lobes within fans. However, it is observed that fan-lobe complex behavior (aggradation or progradation) can be linked to coeval shelf-edge trajectory behavior. This linkage was possible because (1) Washakie Basin was supply-dominated across the entire clinoform from top to bottom, despite times of stronger accommodation influence on some clinoforms, and (2) the sediment transport to deep water was quasi-continuous with consistent slope channel connection between shelf edge and basin floor during most of the sea-level cycle despite significant shelf-edge delta reworking by waves and tides. The latter condition contrasts with the discontinuous (lowstand) sediment delivery for low-supply, accommodation-dominated margins.

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REFERENCES


FIGURE CAPTIONS

FIG. 1.-Location of Washakie Basin in Wyoming showing A) well locations and outcrop exposures and B) a dip-oriented cross-section through the linked fluvial (Lance Fm.) to shelf (Fox Hills Fm.) to deep-marine (Lewis Shale) depositional system, which is crossed by 16 clinothems (modified from Carvajal and Steel 2009 and Olariu et al. 2012). GR: gamma ray; MFS: maximum flooding surface; SE: shelf edge; SP: spontaneous potential; ID: Idaho; MT: Montana; WY: Wyoming; SD: South Dakota; NE: Nebraska; CO: Colorado; UT: Utah.

FIG. 2.-Lobe complexes in one (i.e., Interval 9-3) of five intervals mapped in Clinothem 9 fan. A) Sandstone thickness map showing two main lobe complexes. Cross-sections in depositional B) strike (W-E) and C) dip (N-S) directions. Cross-sections are flattened on the bottom horizon of Interval 9-3. Lobe complexes are thicker in the center and thin laterally displaying a compensational stacking pattern in the strike-section. In the dip direction, lobe complexes are asymmetrical with a convex-up geometry; the lobe complexes are thicker in proximal and thinner in distal parts. D) Lobe complexes interpreted by wireline gamma (GR) log motives showing amalgamated channels (blocky units of low GR), unconfined lobe sheets (upward coarsening GR), and muddy deposits (high GR) in the axis, fringe, and distal fringe of lobes respectively. The southwestern part of the basin was excluded from interpretation due to sparse well data.

FIG. 3.-Three dimensional block diagrams of Clinothem 9, showing sandstone thickness map (on the bottom of block diagram) and the clinoform depositional environment (deltas and submarine fan-lobes) projected onto the top of block diagram at time steps from A) older to F) younger. The evolution of deep-water lobe complexes was linked with the distribution of delta depocenters on the shelf (modified from Olariu et al. 2012). G) Overlap of deep-water lobe complexes. The lobe
complexes vertically stack on each other without significant progradation and lateral shifting. H) Dip cross-section of Clinothem 9. See also Figure 2 for the location of section.

FIG. 4.-Three dimensional block diagrams of Clinothem 10, showing sandstone thickness map (on the bottom of block diagram) and the clinoform depositional environment projected onto the top of the block diagram at time steps from A) older to E) younger. The evolution of deep-water lobe complexes was linked with the distribution of delta depocenters on the shelf (modified from Olariu et al. 2012). F) Overlap of deep-water lobe complexes. The lobe complexes of Clinothem 10 prograde and shift significantly laterally compared to those of Clinothem 9. G) Dip cross-section of Clinothem 10. See also Figure 2 for the location of section.

FIG. 5.-Schematic three dimensional block diagram with projected dip (X-X’) and strike (Y-Y’) cross-sections of clinoforms in A) accommodation-dominated margins. a) sea-level fall; with shelf and shelf-edge incisions with significant sand delivery to deep water. b) sea-level rise; with slumps and muddy failures on slope and basin floor. B) sediment supply-dominated margins. a) sea-level fall; with progradation dominant shelf-edge deltas and submarine fans. b) sea-level rise; with aggradation dominant shelf-edge deltas and submarine fans. Note that in sediment-supply dominated margins, shelf edge deltas are consistently connected with the basin floor by slope channels (more extensive channeling during sea-level fall) at any sea-level stand. In contrast, slope channels in accommodation-dominated margins connect the shelf edge deltas to the basin floor fans only during sea-level fall.
Fig. 1. Rock Springs Uplift

Fig. 3H

Fig. 4G

Fig. 1B

Asquith Marker

Coastal Plain

Base-of-Slope to Basin floor

Mostly coastal plain (Lance Formation)
Mostly sandy deltas, estuaries, and barrier lagoon systems (Fox Hills Formation)

Lance Formation
Fox Hills Sandstone
Lewis Shale and Fox Hills Sandstone
Lewis Shale

Well-log colors:
Sandstone-shale (approximate)

Maximum flooding surface (approximate time line)

Mostly marine shale (Lewis Shale)

C10: Clinothem number
Fig. 2B

SE at MFS 9
SE at MFS 10

Unconfined sandy lobe sheets
Muddy deposits  Well locations

Vertically exaggerated (around 200 times)

Top and bottom of Interval 9-3

FIG. 2.
FIG. 3.
FIG. 4.
FIG. 5.