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How to make a 350-m-thick lowstand systems tract in 17,000 years: The Late Pleistocene Po River (Italy) lowstand wedge

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ABSTRACT

The 350-m-thick succession of the Po River lowstand wedge (Italy) associated with the Last Glacial Maximum (deposited over ~17 k.y) contains stratal architecture at a physical scale commonly attributed to much longer time scales, with complex, systematically varying internal clinothem characteristics. This study investigated clinothem stacking patterns and controls through the integration of seismic reflection data with sediment attributes, micropaleontology, regional climate, eustacy, and high-resolution age control possible only in Quaternary sequences. Three clinothem types are differentiated based on topset geometry, shelf-edge and onlap-point trajectory, internal seismic facies, and interpreted bottomset deposits: type A has moderate topset aggradation, ascending shelf-edge trajectory, and mass-transport bottomset deposits; type B has eroded topset, descending shelf-edge trajectory, and bottomset distributary channel-lobe complexes; and type C has maximal topset aggradation, ascending shelf-edge trajectory, and concordant bottomsets. Type A and C clinothems exhibit reduced sediment bypass and delivery to the basin, whereas type B clinothems are associated with short intervals of increased sediment export from the shelf to deeper water. Clinothems individually span a range of 0.4–4.7 k.y., contemporaneous with significant eustatic and climate changes, but their stacking patterns resemble those found in ancient successions and ascribed to significantly longer durations, indicating that (1) the response time of ancient continental margin–scale systems to high-frequency variations in accommodation and sediment supply could be as short as centuries, (2) even millennial- to centennial-scale stratal units can record substantial influence of allogenic controls, and (3) sandy deposits can be compartmentalized even in a short-duration lowstand systems tract.

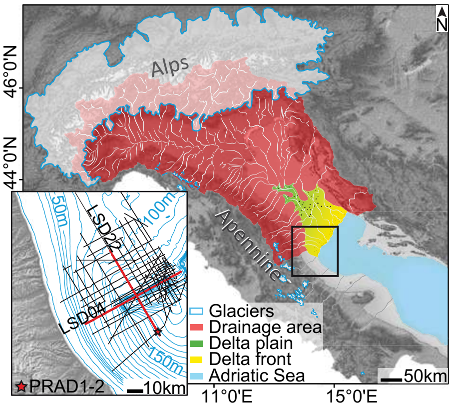

Figure 1. Adriatic Sea physiographic setting during Last Glacial Maximum (LGM) with Alpine and Apennine glacier extent (after Florineth and Schlüchter, 1998; Giraudi, 2011). White lines represent ancestral Po River system (Italy). Inset map: Study area with location of high-resolution seismic data (black lines), multichannel seismic profiles LSD22 and LSD04 (red lines), and PRAD1-2 borehole (red star).

INTRODUCTION

Early sequence-stratigraphic models predicted that third-order lowstand systems tracts (durations of 1–2 m.y.) would be characterized by the deposition of sand-prone channel-lobe complexes topped by the progradation of a mud-prone slope wedge (Vail et al., 1991). This concept was integrated with shoreline- and shelf edge–trajectory analysis to provide a key for predicting the presence of submarine fans within shelf-margin clinothems across a wide range of time scales (Helland-Hansen and Martinsen, 1996; Plink-Björklund et al., 2001; Hampson, 2010). Shelf-margin clinothem sets tend to have shelf-edge progradation rates of <40–60 km/m.y. (Carvajal et al., 2009, and references therein). Much debate continues about the timing and duration of lowstand shelf-margin clinothem and submarine-fan development, their internal architectures (e.g., Sydow and Roberts, 1994; Plint and Kreitner, 2007; Covault and Graham, 2010), as well as the influence of higher-frequency (10^2–10^3 yr) variations in accommodation and sediment supply on clinothem growth.

An excellent data set to address these issues comes from the 350-m-thick Po River (Italy) lowstand wedge, which prograded 40 km into the Adriatic foredeep basin in ~17 k.y. spanning the Last Glacial Maximum (LGM; Fig. 1). We used a grid of high-resolution seismic reflection profiles through this expanded stratigraphic succession to characterize the internal architecture of each component clinothem and tied these observations to a high-resolution micropaleontologic and chronostratigraphic framework constrained by borehole data (Piva et al., 2008). This enabled us to relate clinothem stratal geometries and stacking to independently constrained late Quaternary eustatic and climate changes (e.g., Lea et al., 2002; Monegato et al., 2007) to better understand the relation of clinothem character to high-frequency variations in accommodation, sediment supply, and coarse-sediment bypass to the basin.

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RESULTS

Clinothem Character: Types A, B, and C

The Po River lowstand wedge comprises a set of clinothems with hundreds of meters of relief characterized by cyclic changes in topset geometry, shelf-edge and onlap-point trajectory, seismic facies, and slope and bottomset deposits. Three types of clinothems are recognized:

Type A: Topset strata with continuous, subparallel, high-amplitude reflections that diverge basinward and correlate to bottomset deposits characterized by discontinuous and low-amplitude reflections with internal hyperbolic diffractions (DLAH in Fig. 2); type A clinothems show an ascending shelf-edge trajectory with a maximum vertical component on the order of 10 m (Fig. 2).

Type B: Truncated toplap reflections in the topset connected to semi-continuous, high-amplitude and mounded reflections (SHAM

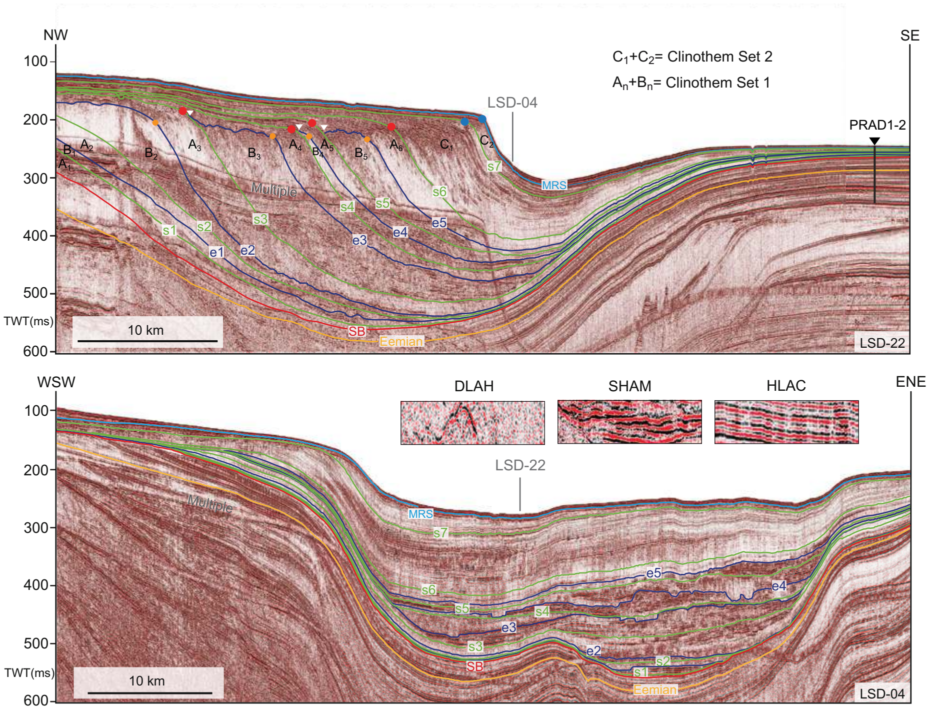

Figure 2. Top: Downdip multichannel seismic profile LSD22 illustrating clinothem geometry along main direction of progradation, Po River (Italy) lowstand wedge. Bottom: Along-strike profile LSD04 highlighting deposits in basin. See Figure 1 for location. Orange horizon marks top of Eemian (ca. 125 kyr B.P.); red horizon is sequence boundary (SB) at base of Po River lowstand wedge; green horizons (*s*) mark surfaces on top of type A and type C clinothems whereas blue horizons (*e*) are on top of type B clinothems; light blue horizon is maximum regression surface (MRS) on top of younger type C_2 clinothem (clinothems are numbered from older to younger). Seismic horizons are tied to PRAD1-2 borehole through high-resolution CHIRP sonar profiles (Item DR5 [see footnote 1]). Red, orange, and blue dots mark shelf edge of type A, B, and C clinothems, respectively. White triangles mark onlap of type B clinothems. Surface s6 marks transition from progradational clinothem set 1 (comprising stacked type A and B clinothems) to aggradational clinothem set 2 (constituted by stacked type C). Insets illustrate basinal seismic facies associated to type A (discontinuous and low-amplitude reflections with internal hyperbolic diffractions, DLAH), type B (semi-continuous, high-amplitude and mounded reflections, SHAM) and type C clinothems (high- and low-amplitude continuous reflections, HLAC) in basin (see also Item DR1). TWT—two-way traveltime.

of Fig. 2) in the bottomset; type B clinothems show a descending shelf-edge trajectory, with a negative vertical component on the order of 10 m across a horizontal distance of 1 to <10 km (Fig. 2). The basal strata of type B clinothems lap on to the underlying bounding surface basinward of and below its rollover point (white triangles in Fig. 2).

Type C: Topset strata with continuous parallel high amplitude reflections that correlate to high- and low-amplitude continuous reflections in the bottomset (HLAC on Fig. 2). Type C clinothems show topset aggradation of up to 15 m at the shelf edge and an ascending shelf-edge trajectory (Fig. 2).

Clinothem Set Stacking Patterns

These clinothem types are systematically distributed. Type A and type B clinothems form couplets that stack within clinothem set 1, characterized by a basinward shifting and essentially flat shelf-edge trajectory, moderate topset aggradation, and the presence of DLAH and SHAM seismic facies in the bottomset (Fig. 2; Item DR1 in the GSA Data Repository[1]). Clinothem set 2 is characterized by two vertically stacked type C clinothems, an ascending shelf-edge trajectory with significant aggradation in the topsets, and draped seismic facies in the bottomsets (Fig. 2; Item DR1). Clinothem set 1 and clinothem set 2 record a total shelf-edge progradation of 40 km.

Chronology, Micropaleontology, and Progradation and Sediment Accumulation Rates

The chronostratigraphic framework of the Po River lowstand wedge has been obtained by calibrating key stratigraphic surfaces to a continuous-recovery borehole (PRAD1-2) drilled in a distal area (Figs. 1 and 2; Items DR2–DR5). The age model shows that the sequence boundary (SB) correlates to ca. 31.8 kyr B.P. (14.6 m downhole), the boundary between clinothem set 1 and clinothem set 2 correlates to ca. 18.0 kyr B.P. (s6, 6.5 m downhole), and the maximum regressive surface (MRS) correlates to ca. 14.4 kyr B.P. (2.5 m downhole; Fig. 3; Item DR4). Micropaleontologic analysis revealed decreasing upward abundances of marine planktic and benthic foraminifera between the SB and MRS, and an increase of as much as two orders of magnitude in both groups of foraminifera above the MRS (Fig. 3).

Based on the age model, progradation and sediment accumulation rates for each clinothem were calculated at the shelf edge (Fig. 3; see the Data Repository for methods). Type A clinothems span millennia and have slower progradation and sediment accumulation rates (≤5 km/k.y. and ≤10.6 cm/yr, respectively); type B clinothems prograde at the centennial scale with the greatest average shelf-edge progradation and sediment accumulation rates (≤15 km/k.y. and ≤22.4 cm/yr, respectively); and type C clinothems show millennial-scale progradation with overall decreasing progradation and sediment accumulation rates through time (≤2.5 km/k.y. and ≤5 cm/yr, respectively). These values match well with sediment accumulation rates measured in the PRAD1-2 borehole (Fig. 3). The greatest rates of progradation and sediment accumulation are recorded in the basin during the LGM chronozone, before the major Alpine glaciers broke down (Fig. 3).

DISCUSSION

Interpretation of Clinothem Sets and Controls

Sequence-stratigraphic analysis within a high-resolution framework enables interpretation of controls on the growth of genetically related clinothems at multiple scales (e.g., Boyd et al., 1989). Within the Po River lowstand wedge, clinothem set 1 and clinothem set 2 compose a genetically related progradational-aggradational (PA) set, characteristic of a lowstand systems tract at the depositional-sequence scale (*sensu* Neal and Abreu, 2009). Our interpretation of the PA set as a lowstand systems tract is also based on (1) seismic-stratigraphic analyses that reveal laterally extensive truncation below and bottomset downlap onto the basal-surface SB (e.g., Fig. 2); (2) the occurrence of an aggradational-progradational-degradational (APD) set seen regionally between the SB and top Eemian surfaces (Fig. 4); and (3) regional mapping by Amorosi et al. (2016) that shows a 200 km basinward shift of coastal onlap from the underlying APD/highstand systems tract; along with (4) retrogradational stacking (R set) of transgressive deposits (Amorosi et al., 2016)

[1]GSA Data Repository item 2017096, Item DR1 (cross section of multichannel seismic profiles), Item DR2 (dates available from the literature and used in the age model), Item DR3 (the age model), Item DR4 (depth and age of the stratigraphic surfaces), Item DR5 (detail of CHIRP profile with stratigraphic surfaces tied to borehole), Item DR6 (clinothem exceedance factors), and Item DR7 (diagram with progradation against time span of each clinothem), is available online at http://www.geosociety.org/datarepository/2017/, or on request from editing@geosociety.org.

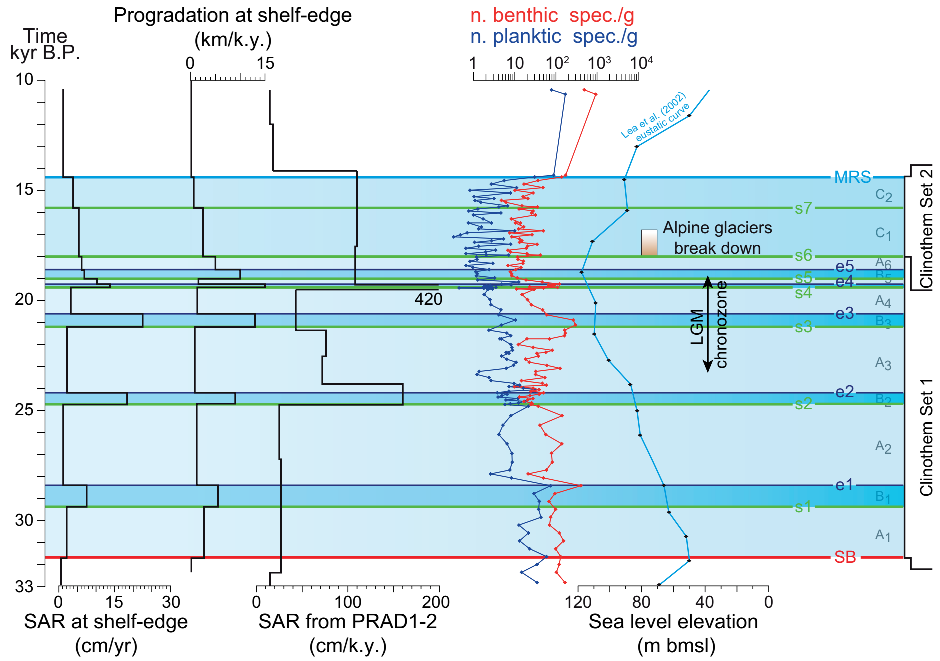

Figure 3. Sediment progradation and accumulation rates derived for each clinothem at shelf-edge and in PRAD1-2 borehole, Po River (Italy) lowstand wedge, with foraminifera abundance (blue, planktic; red benthic; n.—number; spec.—specimens) and eustatic curve (meters below mean sea level [m bmsl]; Lea et al., 2002). Vertical scale is in time (calibrated kyr B.P.). Chronology is based on ^{14}C dating, integrated with tephrochronology, stable isotopes, and biostratigraphy at continuous-recovery borehole PRAD1-2. Type B clinothems (darker stripes) develop at centennial-scale and with higher sediment accumulation rates (SAR, up to 22.4 cm/yr) compared to millennial-scale type A and type C clinothems (lighter stripes). Red line is sequence boundary (SB) at base of Po River lowstand wedge; green lines (*s*) mark surfaces on top of type A and type C clinothems whereas blue lines (*e*) are on top of type B clinothems; light blue line is maximum regression surface (MRS) on top of younger type C2 clinothem (clinothems are numbered from older to younger). Clinothem set 1 spans Last Glacial Maximum (LGM) sea-level fall and lowstand while clinothem set 2 developed during initial phase of post-LGM sea-level rise. Brown box highlights timing of major retreat of Alpine glaciers (Monegato et al., 2007).

above the PA set and outside the study area (Fig. 4). Furthermore, age control shows that the PA set spans the LGM eustatic lowstand (Fig. 3).

Considering the controls on these stratigraphic patterns, within the PA set, clinothem set 1 records progradation with slightly aggrading divergent topsets and essentially flat shelf-edge trajectory (red arrow in Fig. 4) that coincides with the LGM eustatic fall of as much as 30 m (almost entirely compensated by a corresponding amount of subsidence) and with the formation of DLAH and SHAM seismic facies. We interpret DLAH seismic facies as mass-transport complexes (MTCs) and SHAM seismic facies as distributary channel-lobe complexes (DLCs) based on their close resemblance to core-calibrated seismic facies in the Gulf of Mexico (Beaubouef and Friedmann, 2000). Clinothem set 2 records aggradation coupled with ascending shelf-edge trajectory during the post-glacial eustatic rise (Figs. 3 and 4). Above the MRS, a major back-step in the stacking pattern is marked by the establishment of transgressive barrier-lagoon systems on the shelf outside the study area (Fig. 4). Micropaleontological analysis from the PRAD1-2 borehole confirms a marked change in depositional conditions across the MRS from river influenced to open-marine environment (Fig. 3; Piva et al., 2008). Age control compared to the eustatic curve indicates that, at the scale of clinothem sets, eustasy is the main driver that governs change in stacking pattern from progradational, accompanied by the formation of MTCs and DLCs (clinothem set 1), to aggradational, with concordant bottomsets (clinothem set 2), to retrogradational (with barrier-lagoon systems; Figs. 3 and 4).

At the scale of individual clinothems, there is significant debate on the controls of internal architecture of such large-scale systems, most often cast in terms of allogenic versus autogenic factors (e.g., Muto and Steel, 1997). Sediment transport from catchment to sink, however, can act as a nonlinear filter wherein autogenic signals can interact strongly with, or even destroy, allogenic signals (e.g., Paola, 2016). Although independently constrained eustatic and climate variations can provide indications of the contribution of allogenic factors (e.g., Lea et al., 2002; Monegato et al., 2007), the record of such variations is more likely to be preserved where their time scale of variation is longer than a time scale characteristic of the depositional system and when shorelines are migrating in the direction of mean sediment transport (as summarized in Paola [2016]). Such a characteristic time scale can be estimated as $Ti = h/\sigma$ (where h is distributary channel depth and σ is mean subsidence rate; Sheets et al., 2002). Using the data reported in this paper (Fig. 3; Item DR6), we calculate that

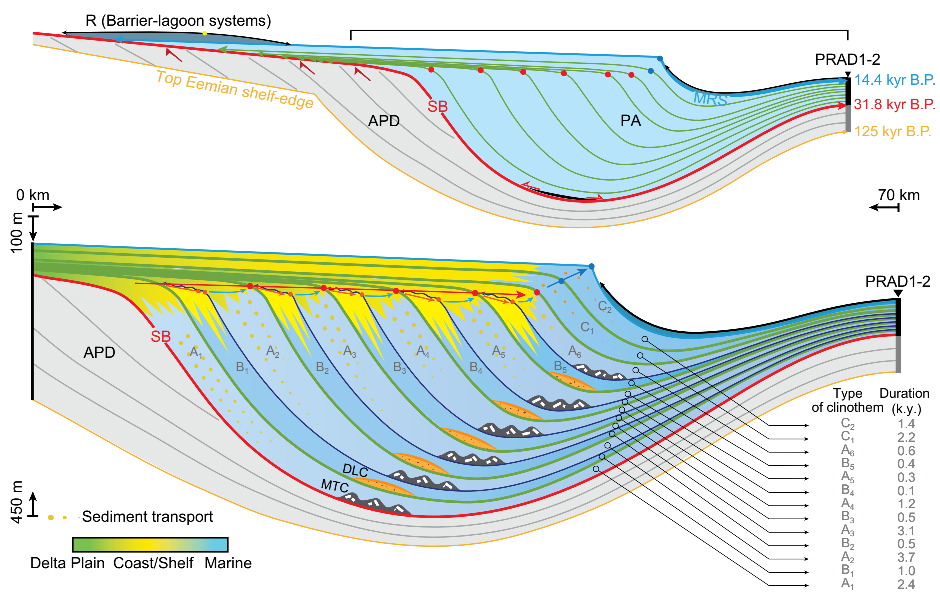

Figure 4. Top: Architecture of Po River (Italy) lowstand wedge characterized by progradational-aggradational (PA) clinothems between sequence boundary (SB) and maximum regressive surface (MRS). Paleo–shelf edge at Eemian time is given for reference along with aggradational-progradational-degradational (APD) set preceding PA set. Atop PA set, lagoonal deposits (R) mark major back-step of paralic environments (Amorosi et al., 2016). Bottom: Detail of lowstand systems tract (PA set) recording millennial- to centennial-scale perturbations with alternating type A (slightly aggradational topset highlighted by light blue arrow and mass-transport complexes [MTCs] in basin) and type B (degradational topset highlighted by orange arrow and distributary channel-lobe complexes [DLCs] in bottomset). Type C develops during initial phase of post–Last Glacial Maximum sea-level rise and heralds greatest topset aggradation.

seven of the 13 individual clinothems (including both type Cs) record time spans that are 1.5× to 5.5× longer than the time scale threshold and thus could have recorded allogenic controls (Items DR6 and DR7). The close coincidence in time of key clinothems, bounding surfaces, and changes in stacking pattern with eustatic and climate changes also suggests a substantial role for allogenic factors—indeed, the very existence and shelf-edge location of the Po River lowstand wedge attests to a significant role of allogenic eustasy.

Implications for Clinothem Timing and Internal Architecture

Our interpretations enable comparisons to other and older stratal successions and have significant implications for the distribution of rock properties. The Po River lowstand wedge formed in 17 k.y., which is ~2× to 1000× shorter than most previously documented examples (see review in Carvajal et al. [2009]). Our calibrated age model also documents shelf-edge progradation rates (Fig. 3) that are ~40× to 400× faster than those studies report for repeated groups of similarly scaled hundreds-of-meters-thick clinothems (with rates of shelf-edge progradation <60 km/m.y.). Many of those studies focused on ancient successions where only lower-resolution age control is available. Given that century-scale resolution is unlikely to be developed for ancient records, we suggest that our case provides valuable insight into the lower end of the range of time spans recorded by such ancient strata and the upper end of shelf-edge progradation rates.

Generalized models of lowstand systems tracts sketched an aggradational sand-prone lowstand fan overlain by a progradational mud-prone lowstand wedge (Vail et al., 1991). These generalizations, although useful at a broad scale, do not fully capture the range of timing and internal architecture of lowstand systems tracts. Our work documents that, within a single lowstand systems tract, one can discern millennial- to centennial-scale clinothems characterized by distinctive geometries and rapid changes in accommodation and both progradation and sediment accumulation rates (Figs. 3 and 4). These systematically stacked hundreds-of-meters-thick shelf-margin clinothems can influence the distribution of hydrocarbon source, reservoir, and seal facies and lead to compartmentalized reservoirs (*sensu* Ainsworth, 2010) at multiple stratigraphic levels within one single lowstand systems tract (type A with MTC, type B with DLC; Fig. 4). In addition, the evolution of the Po River lowstand wedge suggests that sediment delivery to the basin is far from constant and associated with various mechanisms, even within a short-duration lowstand systems tract (Figs. 3 and 4). These findings should prompt reconsideration of depositional and stratigraphic models that assume constant rates of sediment supply to a basin or portray simplistic distributions of rock properties.

CONCLUSIONS

The Po River lowstand wedge records millennial- to centennial-scale changes in systematically stacked 100-m-thick clinothems during a single, short-lived and multistory lowstand systems tract associated with the LGM. The size, stratal geometry, and facies distribution of these clinothems resemble those of clinothems ascribed to 10^5–10^6 yr in ancient sequences, emphasizing that the physical scale of a depositional sequence is independent of the time span of its deposition. Clinothems are grouped into two sets resulting in an essentially flat shelf-edge trajectory accompanied by significant sediment bypass to the basin (clinothem set 1), overlain by an ascending shelf-edge trajectory with increasing amount of sediment sequestered in its topset (clinothem set 2). Moreover, the combination of millennial to centennial perturbations in sediment supply and accommodation during the deposition of clinothem set 1 promoted the formation of DLCs at multiple horizons in the basin, emphasizing that sandy deposits can be compartmentalized even within a single lowstand wedge.

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