

Long cores through the Wilcox Group, Gulf of Mexico, show process variability across different time scales

Jinyu Zhang, William Ambrose, Ronald Steel, and Si Chen

ABSTRACT

Spatial and temporal changes in facies and depositional processes are frequently reported in shallow-marine deltas and estuaries. However, such process variations are less well documented across (and at the time scale of) transgressive–regressive cycles. We use two continuous long cores to describe the transgressive–regressive cycle that is the fundamental building block for the lower and middle Wilcox Group, Gulf of Mexico, and from there, interpret the preferred changes of river, wave, and tide process and signals within the stratigraphic sequences selected in this 7.5-m.y. succession. This fluvial to shallow-water Wilcox Group is of current interest because it forms the topsets of the Gulf of Mexico continental-margin clinothems. Vogelsang 1 Frieda core (2240 ft thick [682.8 m]) shows 14 transgressive–regressive cycles, and the Letco TOH-2A Settlemire core (1730 ft thick [527.3 m]) is divided into 11 such cycles, each ranging from 60 to 352 ft (18.3–107.3 m) thick, and with an estimated duration of ~300–680 k.y. A complete transgressive–regressive cycle, in core, passes upward from wave- or river-dominated regressive delta-front deposits (30–247 ft thick [9.1–75.3 m]) to fluvial or fluvial-tidal channel (sometimes estuarine) deposits (26–108 ft thick [7.9–32.9 m]), and then to wave- or tide-dominated transgressive deposits (9–97 ft thick [2.7–29.6 m]). Each cycle exhibits differing facies at different levels because the proportions of regressive, fluvial, and transgressive intervals vary according to the location on the cross-shelf transect. The entire Vogelsang 1 Frieda core is 48% wave-dominated deposits, 40% river-dominated deposits, and 12% tide-dominated deposits, whereas the entire Letco TOH-2A Settlemire core is 69% wave-dominated deposits, 24% river-dominated deposits, and 7%

AUTHORS

JINYU ZHANG ~ *Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas; jinyu.zhang@beg.utexas.edu*

Jinyu Zhang is a research associate at the Bureau of Economic Geology, The University of Texas at Austin. His expertise is sedimentology, stratigraphy, and source-to-sink numerical modeling. He earned his Ph.D. at The University of Texas at Austin in 2018. He is the recipient of the 2020 Robert Mitchum Award from European Association of Geoscientists and Engineers and the 2018 J.C. “Cam” Sproule Memorial Award from AAPG.

WILLIAM AMBROSE ~ *Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas; william.ambrose@beg.utexas.edu*

William Ambrose is a senior research scientist at the Bureau of Economic Geology, Jackson School of Geosciences at The University of Texas at Austin. His areas of interest include unconventional energy resources, siliciclastic depositional systems, and stratigraphy. Ambrose holds B.S. and M.A. degrees in geosciences from The University of Texas at Austin.

RONALD STEEL ~ *Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas; rsteel@jsg.utexas.edu*

Ronald Steel is a professor and Davis Centennial Chair of the Jackson School of Geosciences at The University of Texas at Austin. He received his B.Sc. degree in 1967 and his Ph.D. in 1971 from the University of Glasgow, United Kingdom. His research aims primarily at using clastic sedimentology to address problems in basin analysis and, in particular, to decipher the signatures of tectonics, sea-level change, climate, and sediment supply in stratigraphic successions.

SI CHEN ~ *School of Earth Resources, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas;*

Copyright ©2022. The American Association of Petroleum Geologists. All rights reserved.

Manuscript received June 19, 2020; provisional acceptance March 23, 2021; revised manuscript received June 9, 2021; final acceptance September 1, 2021.

DOI:10.1306/02072220097

China University of Geosciences, Wuhan, China; sichen720@hotmail.com

Si Chen is an associate professor at the China University of Geosciences in Wuhan. She received her Ph.D. from the China University of Geosciences in Wuhan in 2015. She specializes in shelf-margin sedimentology, delta system, and coastal processes, and has researched various aspects of the paleo-Orinoco shelf margin prism and late Cenozoic South China Sea shelf margin.

ACKNOWLEDGMENTS

We are grateful for the support from the State of Texas Advanced Resource Recovery program at the Bureau of Economic Geology (The University of Texas at Austin), and the RioMAR Consortium (<http://www.jsg.utexas.edu/riomar/>).

DATASHARE 150

High-resolution files of Figures 3 and 4 are available in an electronic version on the AAPG website (www.aapg.org/datashare) as Datashare 150.

tide-dominated deposits. The dominant process in transgressive–regressive cycles (<100 k.y., up to several hundreds of feet thick) is critical for hydrocarbon production and exploration because it defines the type of shoreline and controls the shoreline morphology. We demonstrate the frequent variations of dominant processes across the different time scales and provide a template for fundamental fluvial transgressive–regressive intervals from 25 topset cycles. This is helpful for constructing the essential stratigraphic framework as the basis for internal reservoir architecture.

INTRODUCTION

Repeated shoreline regression and transgression across the shelf builds stratigraphic units bounded above and below by marine shales. These are the fundamental, stratigraphic building blocks of the topset strata of shelf-margin clinoforms and have been called transgressive–regressive (T-R) cycles, high-frequency sequences, or the topset portion of fourth-order stratigraphic sequences (Cross et al., 1988; Mitchum and Van Wagoner, 1991; Embry et al., 2002; Pellegrini et al., 2020; Steel et al., 2020). We choose to use the term “T-R cycles” in this study to emphasize the shoreline movement rather than the sea-level change. In terms of depositional environments, the regressive half-cycle is dominated by fluvial and coeval delta, strandplain, and shelf deposits (Ainsworth et al., 2017), whereas the transgressive half-cycle contains fluvial, estuarine, barrier-lagoon, and shelf ridge deposits (Boyd et al., 1992). The inner segment of the T-R cycle is alluvial and coastal plain deposits, whereas the outer segment is delta-front, shoreface, and open shelf deposits. The landward extent of the marine portion is determined by the landward extent of the shoreline transgression during the upper half-cycle. There is a tendency for the marine, outer segment of the cycle to be short (a few tens of kilometers) in greenhouse periods, but longer (up to 100 km or longer) during icehouse periods (Steel et al., 2020). Generating one T-R cycle commonly takes 10^4 – 10^5 yr, depending mainly on the sediment supply, shelf width, and eustatic conditions (Burgess and Hovius, 1998; Muto and Steel, 2002; Zhang et al., 2017). At a much shorter time scale (< 10^3 yr), the fluvial and marine processes of the shoreline and shelf build and modify the deposits of T-R cycles.

Holocene high-resolution studies of coastal systems show a relatively complicated internal geometry of T-R cycles than the simplified depositional models distilled from early studies on the ancient cycles (Hampson et al., 2008). This complication does not so much affect the boundaries of the T-R cycle but refers mainly to the shorter time scale lateral variability within the cycle, especially involving autogenic shifting, erosion, and sediment reworking by fluvial, wave, and tidal processes during the regressive cross-shelf transit. Recent outcrop and process modeling work have

emphasized that ancient shallow-marine deposits must be analyzed as mixed-process systems in time and space (e.g., Gani and Bhattacharya, 2007; Rossi and Steel, 2016; Ainsworth et al., 2016; Rossi et al., 2018). However, these works focus mostly on subsequence descriptions of the regressive half-cycle.

Recent studies on the Paleocene–Eocene Wilcox group along the topset portion of the Gulf of Mexico margin show that this stratigraphic interval, formed over ~14 m.y., is composed of tens of T-R cycles based on correlations between closely spaced well logs (e.g., Olariu and Ambrose, 2016; Zhang et al., 2016; Ambrose et al., 2018). Sedimentological analysis of long cores also shows the frequent interactions between fluvial, wave, and tide processes within these T-R cycles (e.g., Olariu and Ambrose, 2016; Ambrose et al., 2018; Olariu and Zeng, 2018; Zhang et al., 2019). These recent studies show that the dominant processes of the topset portion of the Gulf of Mexico margin can vary at the time scale of a few hundred thousand years, which is much more frequent than earlier research shows (Fisher and McGowen, 1969; Xue, 1997). However, no previous study quantitatively documents the constraints on the process variability through the Wilcox Group, partly because there are few previously long cores through the entire Wilcox Group. New data from two extremely long cores (~4000 ft in total [~1200 m]) of the lower and middle Wilcox Group provide an opportunity to document the process variability through an ~7-m.y. interval across different depositional environments of both regressive and transgressive half-cycles. These two long cores provide a quantitative understanding of (1) the spatial and temporal scales of T-R cycles in a high-supply, greenhouse setting and (2) the high-frequency mixing of processes at different time scales within these cross-shelf cycles.

TEXAS WILCOX GROUP BACKGROUND

The upper Paleocene to lower Eocene Wilcox Group overlies the mudstone-dominated Midway Group and in turn, progrades over the Cretaceous carbonate shelf margin of the Gulf of Mexico (Figure 2). The total duration of the Wilcox Group deposition is ~14 m.y., which can be divided into the lower (~4.2 m.y.), middle (~3.3 m.y.), and upper Wilcox Group (~6.8 m.y.) (Galloway et al., 2011). The

Texas Wilcox Group is a clastic succession up to 3000 m thick, representing the topset of the Gulf of Mexico continental margin prism. The topset depocenter shifted from the eastern Rockdale delta system (Fisher and McGowen, 1969) to the western Rosita delta system (Edwards, 1981) during the deposition of the lower to upper Wilcox Group (Figure 1).

The onshore Texas Wilcox Group has long been a topic of clastic sedimentology study. It was the type area that helped Fisher and McGowen (1969) to originate the classic concept of depositional systems. It was also one of the type areas in which clastic shelf margins were first documented (Edwards, 1981; Winker, 1981). Many early works relied on well-log correlations to construct the stratigraphic framework and to understand the architecture and evolution of deltaic systems (e.g., Edwards, 1980, 1981; Bebout et al., 1982; Xue and Galloway, 1995; Xue, 1997). For example, based on well-log patterns, Edwards (1981) proposed that the upper Wilcox is composed of four linked sedimentary facies associations: from prodelta deposits to coarsening-upward delta-front deposits to distributary channel and mouth-bar deposits to interdistributary bay deposits. Recent studies have

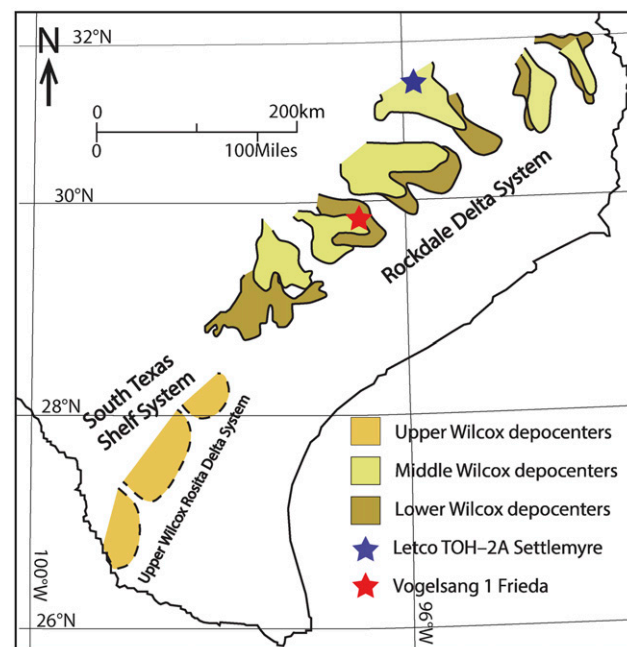


Figure 1. Paleogeographic map showing a snapshot of lower and middle Wilcox deltaic systems and the locations of the two studied long cores (Letco TOH-2A Settlemeyre and Vogelsang 1 Frieda) (paleogeography modified after Fisher and McGowen, 1969; Edwards, 1981; Olariu and Zeng, 2018; Zhang et al., 2019).

begun to use high-resolution core descriptions to better understand the complexity and mixing of fluvial, wave, and tidal processes in these ancient shorelines, benefiting from the extensive core collection at the Bureau of Economic Geology at The University of Texas at Austin (e.g., Olariu and Ambrose, 2016; Ambrose et al., 2018; Olariu and Zeng, 2018; Zhang et al., 2019). These works have documented the high-frequency process variability at the scale of fundamental, fourth-order sequence (up to 300 ft [tens of meters] thick, hundreds of thousands of years duration), especially for the regressive deltaic deposits (Zhang et al., 2016). For example, Olariu and Ambrose (2016) documented the transition of deltaic deposits across growth faults from wave and tide influenced to wave dominated. Olariu and Zeng (2018) documented the mixing of fluvial and wave-dominated shelf deposits deriving from hyperpycnal processes (Mulder et al., 2003).

METHODOLOGY

Data

Two continuous cores in the lower and middle Wilcox Group, Vogelsang 1 Frieda and Letco TOH-2A Settlemire, are used to document sedimentary facies, interpreted process regimes, and the evolution of the upper Paleocene Rockdale deltaic systems (Figures 1, 2). The 2240-ft (682.8-m) Vogelsang 1 Frieda core from Colorado County, Texas records a stratigraphic entry-point succession for major sediment influx (Figure 3). The 1730-ft (527.3-m) Letco TOH-2A Settlemire core from Leon County, Texas represents off-axis, primarily interdeltic deposits (Figure 4).

Sedimentological Analysis

Key sedimentological data include bed thickness, grain size, sedimentary structures, abundance of organic matter, and trace fossils, all collected at 0.4 to 4 in. (centimeter–decimeter) scale. Both the type of trace fossil and bioturbation intensity are described (Pemberton et al., 1995; Marchand et al., 2015; Xu et al., 2017). The dominant processes (i.e., fluvial currents, tidal currents, and waves) are interpreted based on the lithofacies and the context of the depositional environments. High-resolution core descriptions and

interpretations of dominant processes and depositional environments of two cores are reported in Figures 3 and 4 (see high-resolution files of Figures 3 and 4 in the supplementary material available as AAPG Data-share 150 at www.aapg.org/datashare). The evolution and mixing of the dominant and influential processes through the lower and middle Wilcox are analyzed. Based on the results of the two studied cores and building on recent published sedimentological analyses of ~30 cores from the Texas Wilcox Group (i.e., Olariu and Ambrose, 2016; Zhang et al., 2016, 2019; Ambrose et al., 2018; Olariu and Zeng, 2018), this paper reports and clarifies the depositional model of Wilcox wave- and river-dominated regressive deposits, fluvial channel deposits, and transgressive deposits.

Selecting Regressive and Transgressive Half-Cycles

Maximum flooding surfaces (MFSs) are used to divide the sequences (following Galloway, 1989) into T-R cycles (which establish sequence boundaries) (Embry and Johannessen, 1993; Embry, 1995), because it is significantly easier to identify MFSs in one-dimensional (1-D) core data (Figures 3–5). The MFSs are defined by the transition from an upward-fining and increasingly distal marine retrogradational succession to an upward-coarsening and shallowing, progradational shoreline succession. The lithofacies associated with the MFS vary from proximal to distal. In proximal reaches, it is represented by inner-estuary bioturbated mudstone or interbedded bioturbated mudstone and sandstone from the backstepped shoreface and lies below distributary channels or upward-coarsening delta-front deposits of the overlying regressive unit. In distal locations, it is dominated by structureless black mudstone, which can be distinguished from the overlying and underlying bioturbated mudstone. Locally, the succession below the MFS is often composed of structureless fine- to medium-grained sandstones and transgressive shell lags. In some distal cases, highly cemented mudstone and siltstone were also observed, meeting the description of a condensed zone below the MFS (Shaffer, 1990).

It can be more difficult to define the maximum regressive surface in cored successions (Figure 5), but it generally occurs in the transition from an upward-coarsening succession (i.e., the regressive half-cycle) to the upward-fining succession (i.e., the

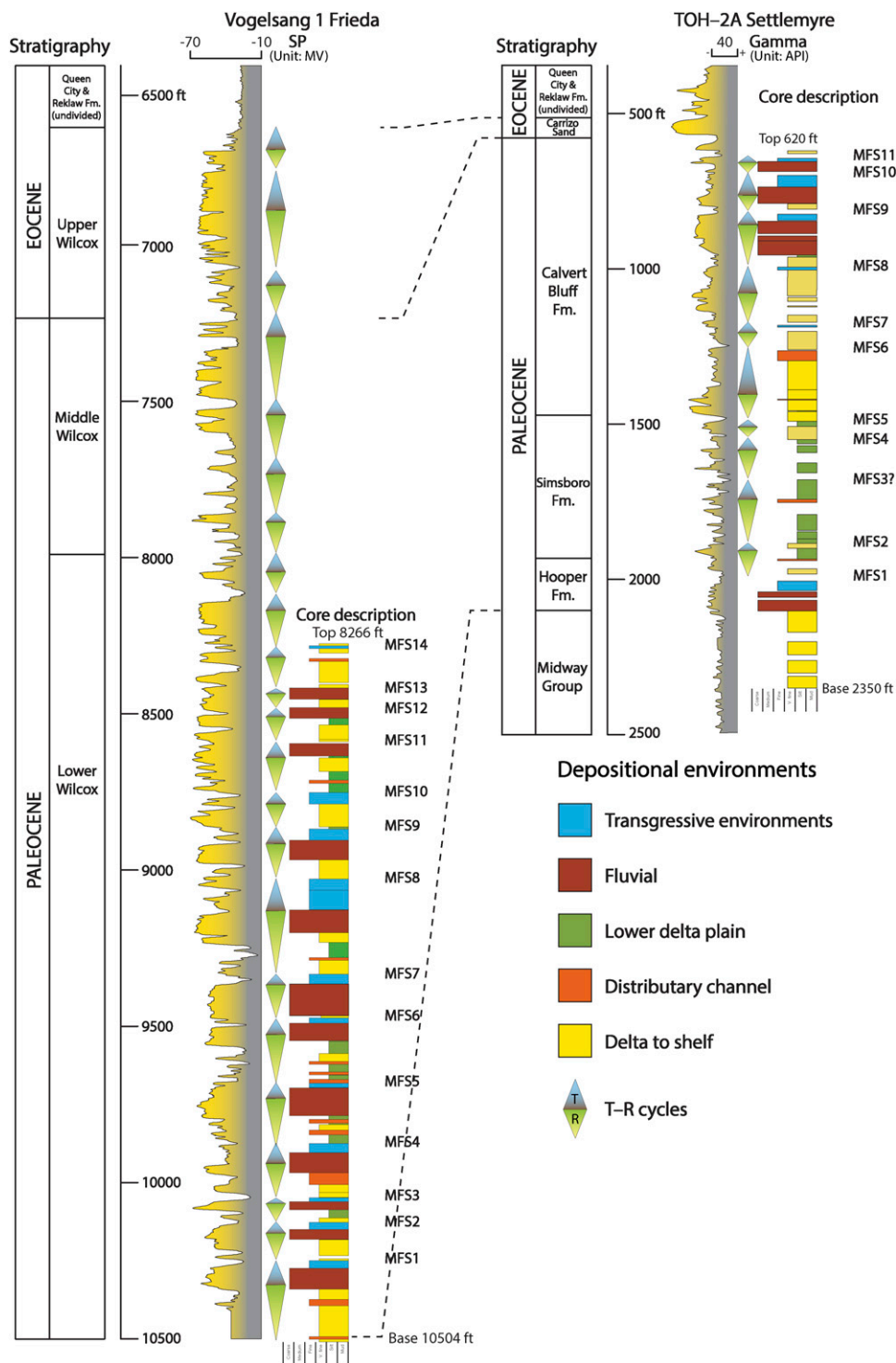


Figure 2. Stratigraphy, wire-line logs, and interpretation of both transgressive-regressive (T-R) cycles and depositional environments for two studied wells (Letco TOH-2A Settlemyre and Vogelsang 1 Frieda). The transgressive half-cycle contains fluvial, estuarine, barrier-lagoon, and shelf ridge deposits (Boyd et al., 1992). Fm. = Formation; MFS = maximum flooding surface; SP = spontaneous potential logging.

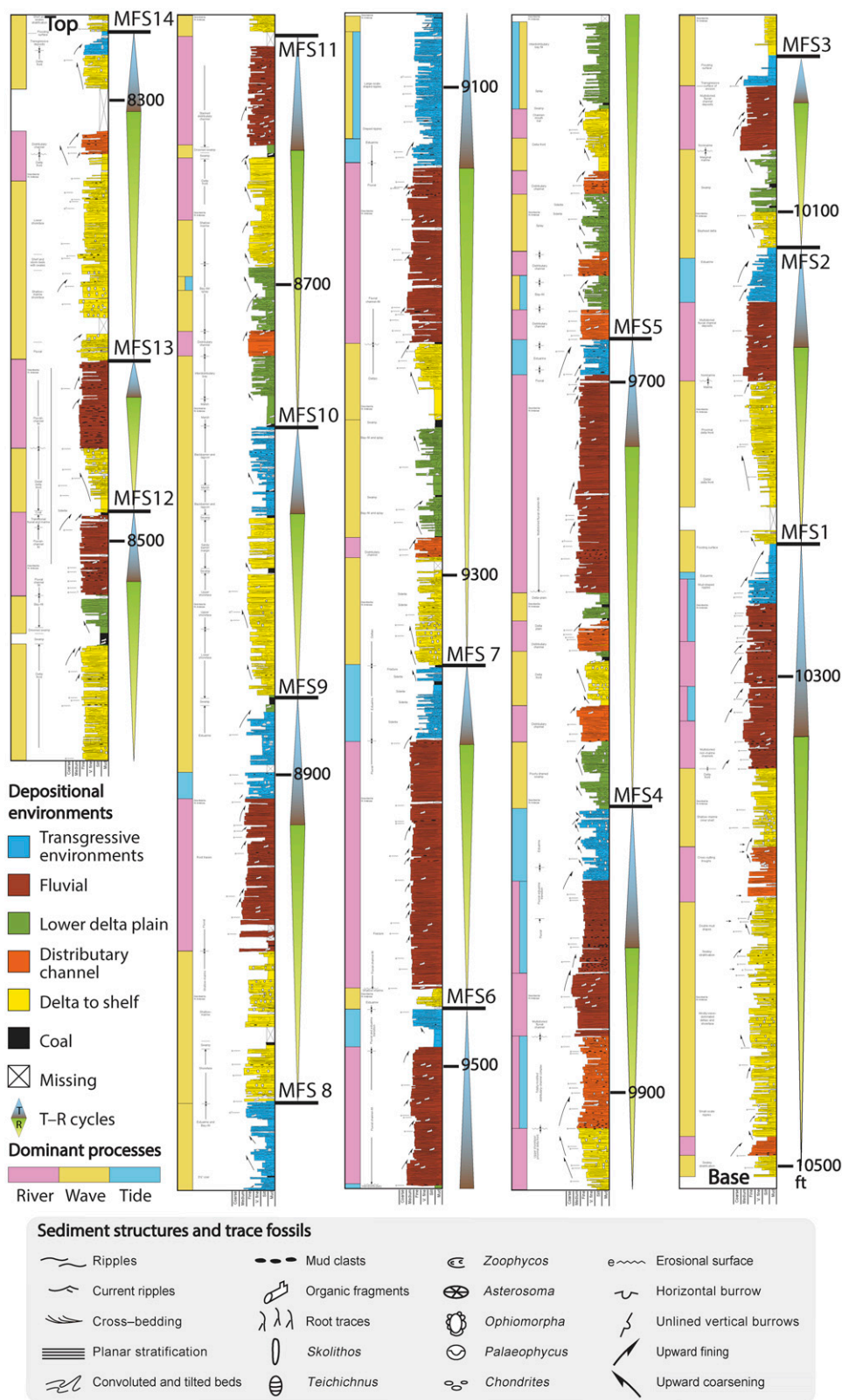


Figure 3. Core descriptions of Vogelsang 1 Frieda, with interpretations of maximum flooding surfaces (MFS), depositional environments, and dominant processes. T-R = transgressive-regressive. A high-resolution version of this figure can be seen in AAPG DataShare 150 at www.aapg.org/datashare.

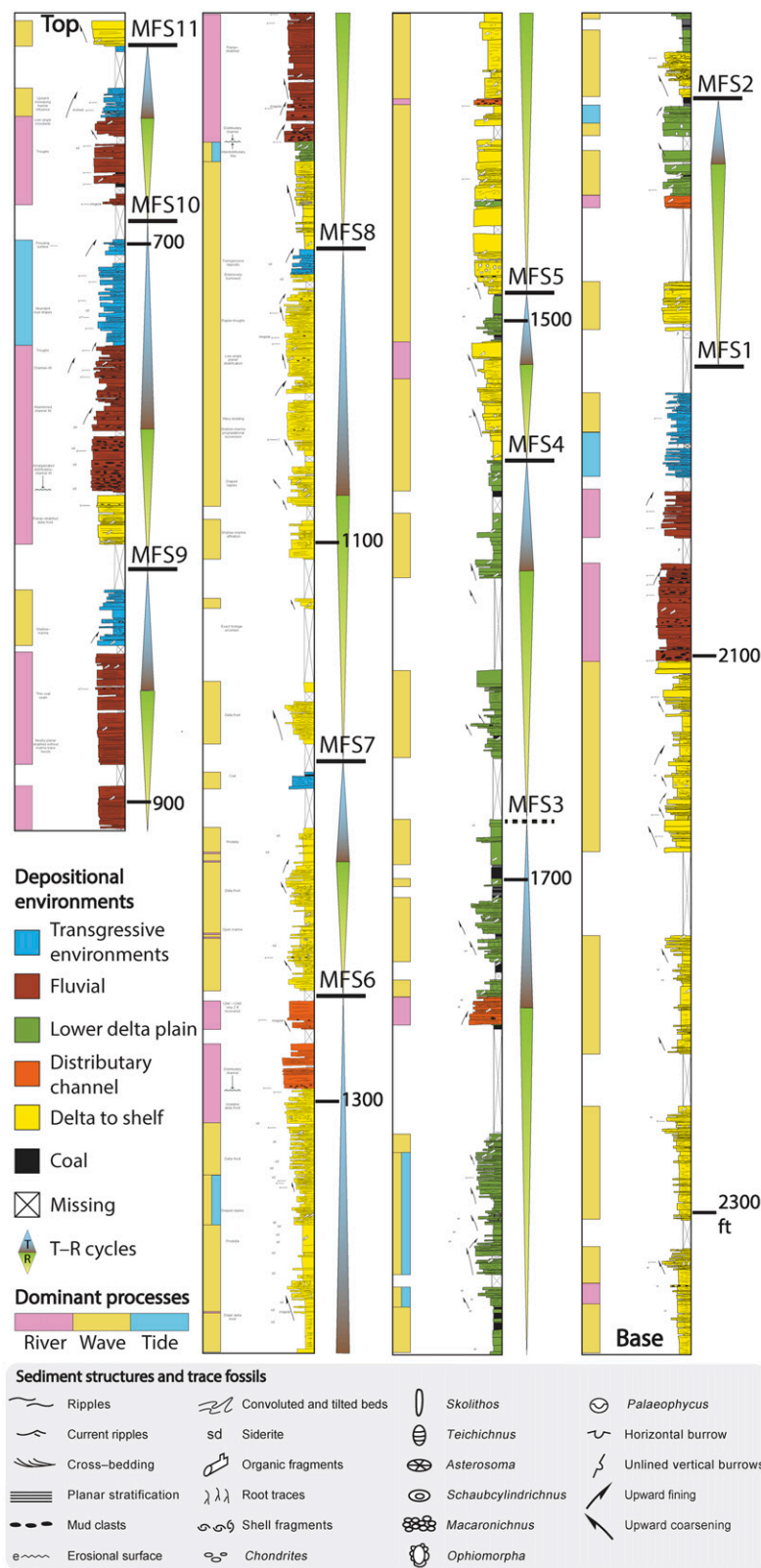


Figure 4. Core descriptions of Letco TOH-2A Settlemyre with interpretations of maximum flooding surfaces (MFS), depositional environments, and dominant processes. T-R = transgressive-regressive. A high-resolution version of this figure can be seen in AAPG Datashare 150 at www.aapg.org/datashare.

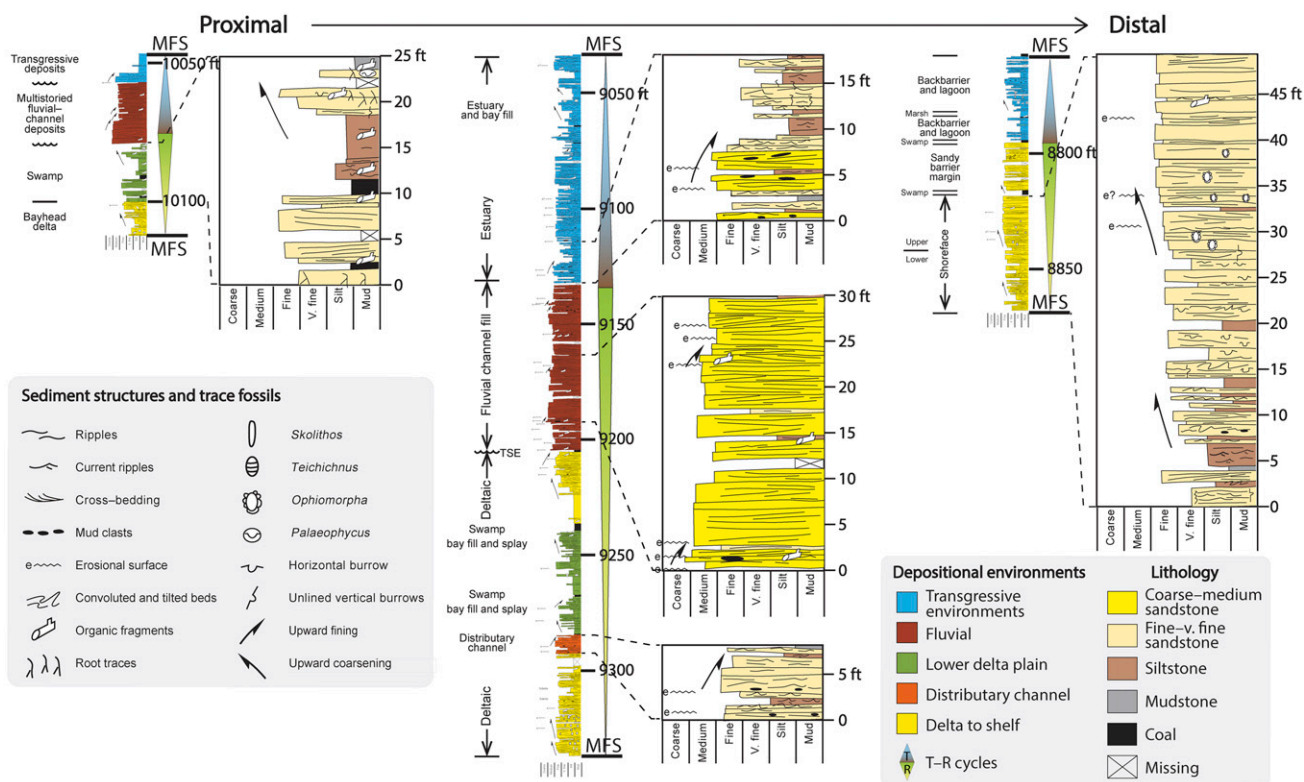


Figure 5. Examples of three transgressive-regressive (T-R) cycles from Vogelsang 1 Frieda. MFS = maximum flooding surface; TSE = transgressive surface of erosion; V. fine = very fine.

transgressive half-cycle). In proximal areas, the sharp or erosive base of channel deposits is commonly interpreted as the maximum regressive surface. However, it can be difficult to decide whether the surface is a regionally extensive boundary or the base of a local fluvial and distributary channel. Multiple channel bases can be present in one T-R cycle, partly because successively stacked regressive “parasequences” can have distributary cappings and partly because the uppermost channel may have been eroded during regression but filled as an estuarine channel during transgression. In distal marine shelf reaches, the maximum regressive surface is mostly interpreted based on the changing trends in grain size, which can be unclear in these low-energy environments.

Between two successive MFSs, the T-R cycle is characterized by an upward-coarsening to blocky to upward-fining succession. Each cycle of the Wilcox Group is commonly tens of feet thick (Zhang et al., 2016), the thickness controlled by the modest amplitude of greenhouse sea-level change (Miller et al., 2005; Sømme et al., 2009; Miller et al., 2020). The

thickness increases toward the shelf margin due to increasing water depth. The proportion of fluvial and distributary channel deposits decreases from proximal to distal. The regressive half-cycle is commonly thinner in the proximal area but thicker in the distal area. The sandstone proportion of the transgressive half-cycle is commonly higher than that of the regressive half-cycle because of the thick muddy prodelta deposits in the latter.

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS: DELTAIC, FLUVIAL, AND ESTUARINE DEPOSITS

Regressive Intervals

Wave-Dominated Delta-Front to Prodelta and Shelf Deposits

The upward-coarsening succession above the MFS is usually tens of feet thick (Figure 6). It transits upward from bioturbated mudstone to interbedded mudstone

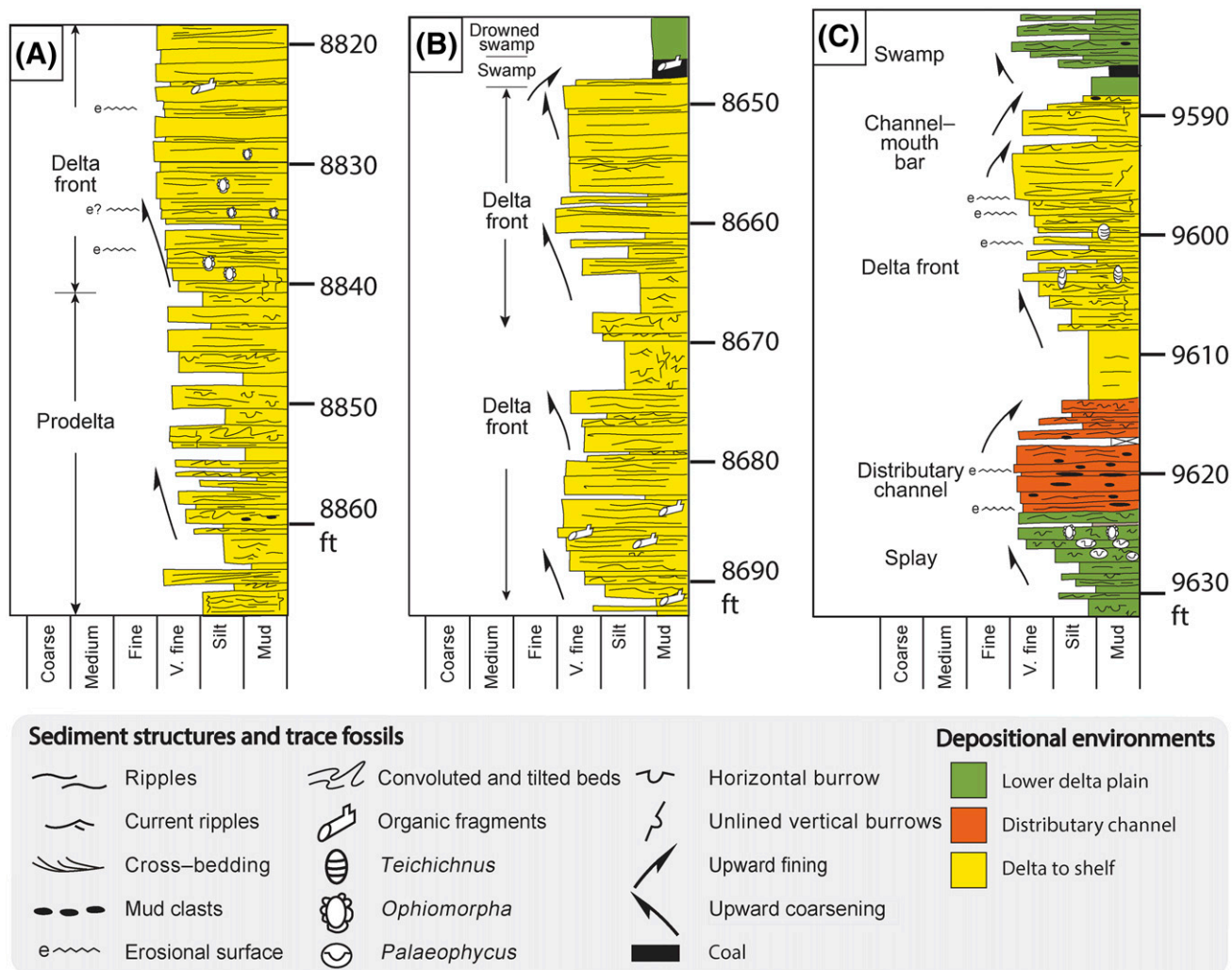


Figure 6. Examples of regressive deposits. (A) Wave-dominated delta-front deposits, (B) several subunits or parasequences of delta-front deposits, and (C) alternating delta plain and river-dominated delta-front deposits. V. fine = very fine.

and sandstone to thicker beds of sandstone. The sand proportion, organic content, and thickness of each set or bed increase upward. Symmetrical and asymmetrical ripples are observed within the silty to sandy beds (Figure 7E, F). Sandstone beds with multiple sets are usually 0.5–4.0 ft (0.15–1.2 m) thick, showing low-angle lamination, hummocky and swaley stratification (HCS and SCS), and trough cross-strata (Figure 7A, B). Considering the common scale of HCS and SCS (>3 ft wide and 1–20 ft thick [>0.9 m wide and 0.3–6.1 m thick]), it is challenging to differentiate HCS from trough cross-strata when using only cores. However, a guiding principle is that the slope of laminae in a set of HCS and SCS decreases upward, in contrast to the downlapping and steepening-upward laminae of subaqueous dunes. The bases of the

sandstone beds are sharp or erosional, and these beds overlie bioturbated mudstone or siltstone (Figure 7G). Soft-sediment deformation sometimes underlies the laminated sandstone (Figure 7C). In rare cases, the erosional surface is filled with mudstone (Figure 7I). Both bioturbation diversity and intensity decrease upward. The dominant trace fossils change upward from *Cruziana* ichnofacies to *Skolithos* ichnofacies. It is common for the lowermost muddy succession to be pervasively bioturbated (bioturbation index [BI] = 3–6). The bioturbation can destroy the original laminations of the silty and muddy intervals (Figure 7H). In contrast, only limited *Ophiomorpha* and *Paleophycus* are observed in the sandy intervals (Figure 7D).

The repeated upward-coarsening successions change vertically from wave-influenced prodelta to

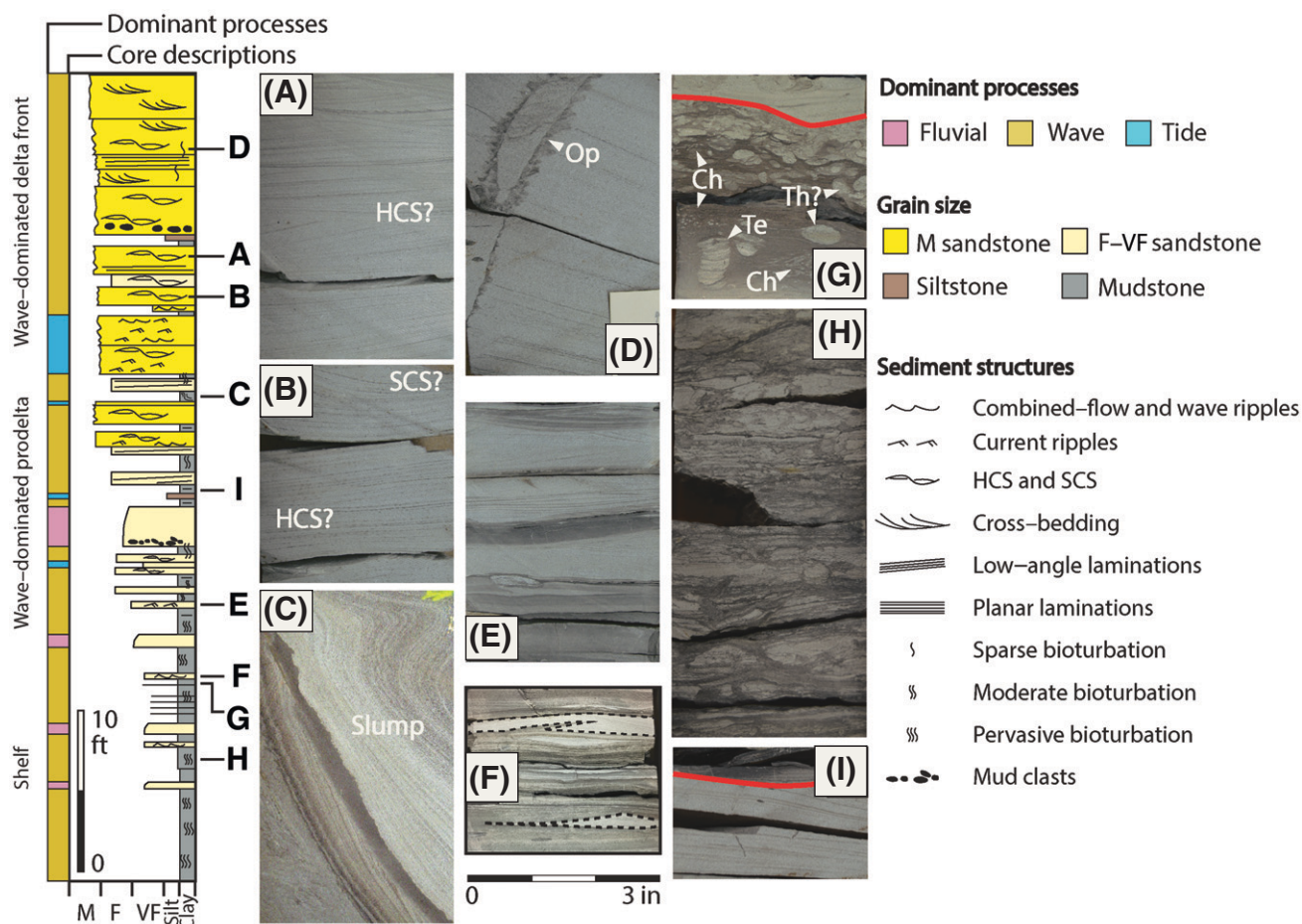


Figure 7. Left: Facies succession of wave-dominated delta-front deposits (with some tidal and fluvial influence) and locations of core photographs. Right: (A) Clean, very-fine-grained (VF) sandstone, interpreted as hummocky cross-stratification (HCS); (B) clean, VF sandstone, interpreted as HCS and swaley cross-stratification (SCS); (C) slump deposits; (D) laminated fine-grained (F) sandstone with *Ophiomorpha* (Op); (E) heterolithic interval with asymmetric current ripples; (F) heterolithic interval with combined-flow ripples; (G, H) muddy intervals with pervasive bioturbation; and (I) mudstone overlying the erosive surface. Ch = *Chondrites*; M. = medium; Te = *Teichichnus*; Th = *Thalassinoides*.

wave-dominated delta-front deposits. The increase in sandstone proportions and organic matter upward strongly suggests an approach to the river mouth. The bioturbated muddy intervals with rare ripple laminae are interpreted as prodelta deposits formed in the relatively low-energy environment below the storm wave base. The upper part of this succession alternates between fair-weather and storm beds. The fair-weather beds are characterized by mudstone to very-fine-grained sandstone with moderate to high bioturbation and ripple laminae. The storm deposits are composed of low-angle laminations and HCS and SCS fine-grained sandstones. Rip-up clasts at the sharp bed bases and soft-sediment deformation structures below the sharp bases are possible storm signals.

The suspension feeding behavior of trace fossils (e.g., *Ophiomorpha*) is also evidence of high-energy storm events. The intensity of the bioturbation depends on the frequency and severity of the storm.

Tidal Influence on the Wave-Dominated Delta-Front—

Thin mud-draped sandstones, sometimes with clear double mud drapes, are prominent within the clean storm beds and fair-weather beds. The laminated heterolithic units are several inches thick, and some of them show bioturbation on the top. The mud drapes can be present (1) directly above an erosional surface within a mud-rich interval (Figure 8C), (2) between storm beds (Figure 8B), and (3) above the storm beds (Figure 8D). In rare cases, they are found below

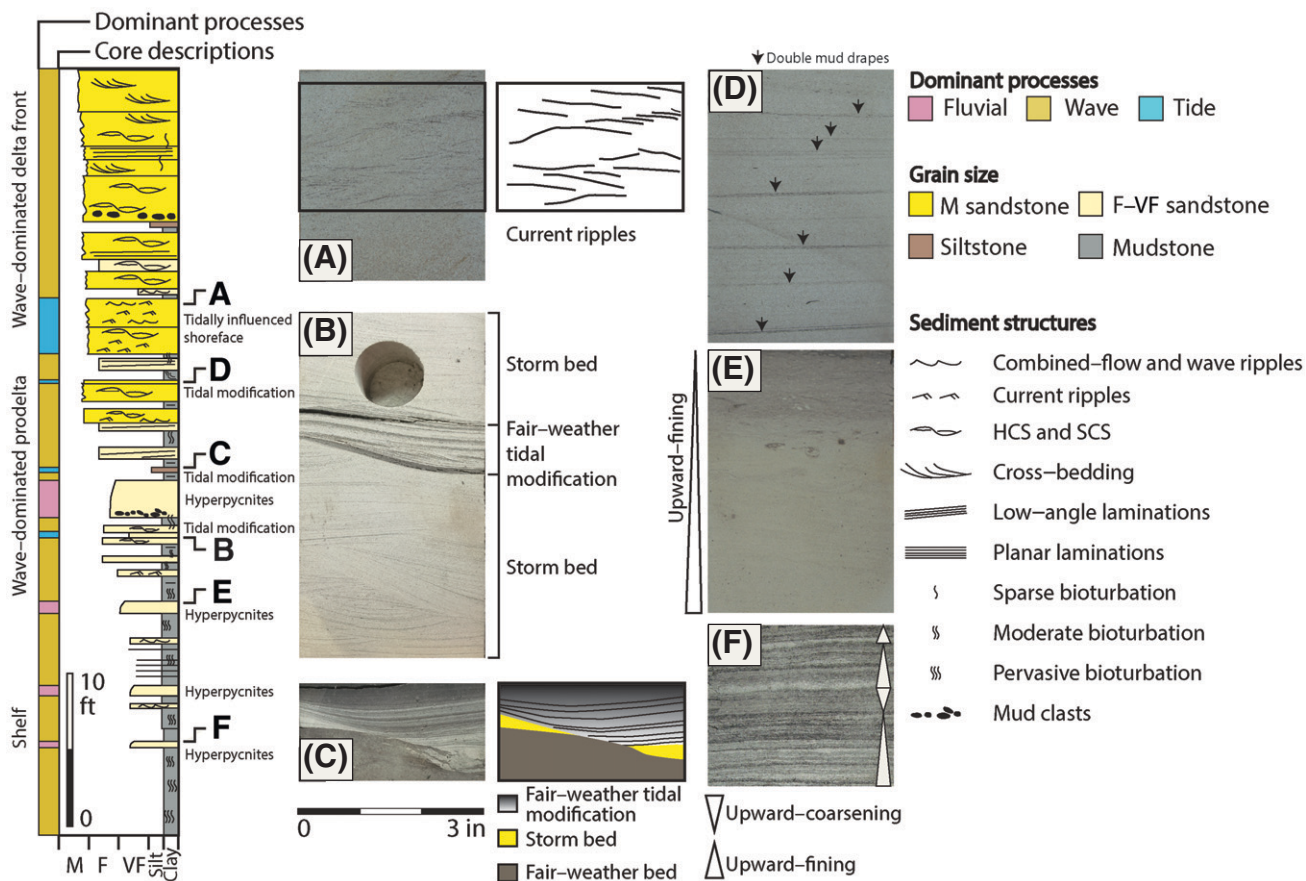


Figure 8. Left: Facies succession of wave-dominated delta (with some tidal and fluvial influence) and locations of core photographs. Right: (A) Current-rippled very-fine-grained (VF) sandstone; (B) possible tide-influenced rhythmites between two fine-grained (F) sandstone layers with hummocky cross-stratification; (C) tide-influenced rhythmites overlying F sandstone beds and wave-scour surface; (D) F sandstone with (double) mud drapes; (E) graded bed from VF sandstone to mudstone; and (F) heterolithic interval with VF sandstone, siltstone, and mudstone. Sandstone displays subtle normal grading. (B), (C), and (E) are modified from Zhang et al. (2019). M = medium.

clean storm beds. It is unlikely that all mud-draped siltstones and sandstones are generated by tidal processes. However, some delicate, organized, cyclic mud drapes are interpreted as the result of tidal slack water. The “random” presence of tidal mud drapes within storm beds is due to the diurnal character of tidal signals, compared to the much less frequent occurrence of storm events. The variation in the preservation of tidal signals is controlled by the frequency and duration of storms and the strength of tidal currents. The thin tidal deposits are best preserved during fair-weather periods and are likely preserved on the prodelta or distal reaches of the delta-front. Some researchers suggest that they can form before a storm, interstorm, or at the waning stage of storm events (Wei et al., 2016).

Fluvial Influence on the Wave-Dominated Delta-Front—Inversely or normally graded fine-grained beds (siltstone to very-fine-grained sandstone) and high amounts of organic matter occur within the fair-weather beds (bioturbated mudstone or siltstone) in distal prodelta to shelf settings (Figure 8E, F). The thickness of the graded beds varies from a few inches in the distal locations to up to ~0.5 ft (0.15 m) in the proximal locations. The lower half of the normal graded beds are very-fine-grained sandstones with occasional rounded mud clasts. The upper half has a matrix of mudstone to siltstone, and locally contains abundant rounded small pebbles and mud clasts. In addition to the graded beds, thick (0.3–1.0 ft [0.09–0.3 m]), structureless sandstone beds were evident within the prodelta deposits that also contain

organic matter and mud chips. The coarser grain size and absence of bioturbation cause these structureless sandstones to stand out from the overlying and underlying bioturbated mudstone and siltstone. Trace fossils are rarely observed (BI = 0–1) and are mostly found on the top of the sandstone, if present.

Both the graded and structureless sandstone can be interpreted as hyperpynites associated with river flooding. This interpretation is mainly based on bed discreteness, coarse-grain size in the distal area, and the absence of bioturbation. The low-intensity bioturbation is linked to strong fluvial energy and stress conditions caused by salinity and turbidity variations (Bhattacharya and Walker, 1991; Bhattacharya and MacEachern, 2009). These hyperpynites are mostly preserved in the distal reaches of wave-dominated deltas because proximal graded beds are not easily preserved in a shallow wave-dominated setting. It is possible that the outrunner hyperpynites were buoyantly aided by wave action, as documented elsewhere by Mulder et al. (2003) and Bhattacharya and MacEachern (2009).

River-Dominated Regressive Intervals

Lower Delta Plain (Interdistributary Bay, Swamp, and Crevasse Splay)—This facies association is characterized by successions that are a few feet thick, with mixed mudstones, siltstones, very-fine-grained sandstones, and thin coals (Figures 6, 9). It is commonly coarsening-upward, transitioning from mudstone-dominated up to sandstone-dominated heterolithics. The bioturbation intensity in sandy intervals is rare to moderate (BI = 0–3), whereas that in muddy intervals is moderate to intense (BI = 3–6). Mixed *Cruziana* and *Skolithos* ichnofacies are present. The trace fossils are restricted to *Paleophycus*, *Chondrites*, *Planolites*, *Phycodes*, and *Arenicolites* (commonly 1–3 in. in length [0.025–0.076 m]). The sandstone shows both current- and wave-generated ripple lamination with mud drapes (Figure 9F–H). The current ripples can be erosional and bidirectional. Organic lenses and plant roots are evident in the sandstone. The mudstone is also organic rich and is sometimes enriched to coal beds (0.2–0.8 ft thick [0.06–0.24 m]) (Figure 9E).

This facies association is interpreted as lower delta-plain deposits, which are commonly incised by distributary channels and overlie mouth-bar or delta-front deposits (Figures 5, 6, 9). The rarity and small size of the trace fossils, the assemblage of the

sedimentary structures, and the richness of organic matter suggest a low-energy brackish water environment. The interaction of tidal and wave processes and the presence of associated coal and plant roots indicate a subaerial interdistributary embayment on the delta-plain environment, which is laterally associated with the proximal delta-front.

River-Dominated Delta-Front to Prodelta—This facies association is up to 30 ft (9.1 m) thick and shows an upward-coarsening (Figures 6, 9) from bioturbated mudstone and siltstone up to heterolithic strata and thick sandstone. The lowermost bioturbated beds are overall mudstone dominated but are sometimes interrupted by ripple-laminated sandstone (1–2 in. thick [2.5–5.1 cm]) (mostly starved ripples) or graded beds (3–7 in. thick [0.076–0.178 m]). They are commonly composed of several thin, coarsening-upward successions (2–7 ft thick [0.6–2.1 m]). The bioturbation is dominated by diverse *Cruziana* ichnofacies. Soft-deformed siltstone and sandstone (up to 1 ft thick [0.3 m]) are occasionally observed within the mudstone beds. The sandstone content and thickness of the heterolithics increase upward, whereas the bioturbation intensity decreases upward. The sandstone layers are commonly 2–6 in. (5.1–15.2 cm) thick, with current and combined-flow ripple laminae (Figure 9B). The mudstone layers are 2–8 in. (0.051–0.203 m) thick and bear *Cruziana* and *Skolithos* ichnofacies such as *Condrites*, *Planolites*, *Thalassionoides*, *Asterosoma*, and *Teichichnus*. The uppermost fine-grained sandstones are flat laminated or structureless and sometimes softly deformed (Figure 9A). They are also organic rich but rarely bioturbated.

This general upward-coarsening succession is interpreted as river-dominated prodelta to delta-front deposits. The mudstone-dominated facies and presence of *Cruziana* ichnofacies in the lowermost beds indicate an overall low-energy environment. The presence of graded and soft-deformed beds also suggests that these quiet environments were frequently interrupted by turbidite-like flood and storm wave events. The interbedding of structured sandstone and bioturbated mudstone represents episodic (maybe seasonal) variations of flood events. The increasingly structured sandstone, lower-intensity bioturbation, and higher amount of organic content upward indicate a more proximal depositional position toward the river mouth. The uppermost beds,

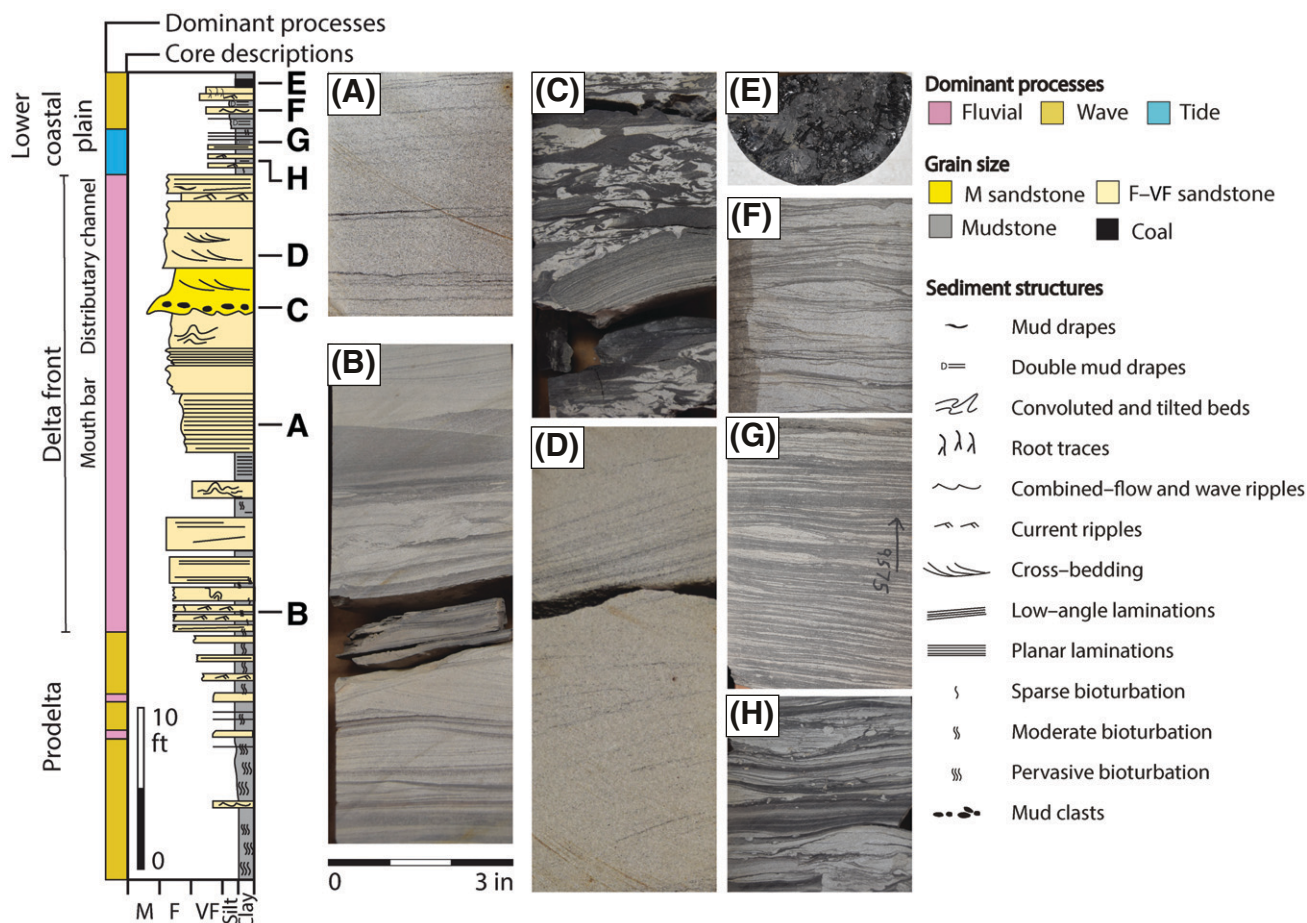


Figure 9. Left: Facies succession of river-dominated deltaic deposits with some tide and wave influence and locations of core photographs. Right: (A) Flat to very-low-angle, laminated, fine-grained (F) sandstone; (B) rippled very-fine-grained (VF) to F sandstone alternating with siltstone; (C) F sandstone with mud clasts; (D) cross-bedded F sandstone; (E) coal; and (F–H) deposits representative of the lower coastal plain, with alternating VF sandstone and mudstone. Pin-striped sandstone contains combined-flow ripples. Sparse to moderate bioturbation is *Chondrites* and *Planolites*. M = medium.

dominated by laminated sandstone and abundant in organic matter, are the most proximal location to the river mouth.

As key parts of the river-dominated delta-front, river mouth-bars, and distributary channel can develop an upward-coarsening (mouth-bars) to the upward-fining, cross-bedded (distributary channels) interval near the top of the delta-front, each of these parts can be independently present within a narrow core of the regressive half-cycles (Figures 6, 9). Each is commonly a few feet thick, up to 20 ft (6.1 m). The upward-coarsening succession is sandy and thickening upward, transiting from mudstone to upper very-fine- to upper fine-grained sandstone. The mudstone ranges from mostly laminated to structureless and locally bioturbated. The bioturbation decreases upward and

changes from *Cruziana* to *Skolithos* ichnofacies. The sandstone is dominated by parallel laminations with combined-flow ripples, carbon fragments, and mud clasts (1–2 in. long) (2.5–5.1 cm). The upward-fining succession commonly truncates the underlying finer-grained marine deposits, which have an erosional base. The base often contains subangular to rounded mud clasts (Figure 9C) and sometimes has fluid mud layers. The organic-rich, fine- to medium-grained sandstone within the upward-fining succession is commonly structureless and either laminated or cross-bedded, with poor to moderate sorting. It is associated with sparse bioturbation locally, mostly vertical trace fossils such as *Ophiomorpha* or *Skolithos*. Both upward-coarsening and upward-fining successions may transition to heterolithic deposits.

The heterolithic deposits have abundant double mudstone drapes and bipolar current ripples, which have slightly higher bioturbation ($BI = 0\text{--}3$) and contain *Cruziana* or *Skolithos* ichnofacies.

The upward-coarsening succession is interpreted as mouth-bar deposits, whereas the upward-fining succession is interpreted as distributary channel or terminal distributary channel deposits (Olariu and Bhattacharya, 2006) due to the dominance of upper flow regime sediment structures and the scarcity of bioturbation. Mouth-bars accumulated in front of distributary channels, both of which prograded into the shallow-marine basin. The mouth-bar is proximal to the river input, as indicated by the abundance of mud clasts, organic matter, soft-sediment deformation, and upper flow, plane-parallel laminations (Lindsay et al., 1984; Dixon et al., 2013). Distributary channels are easily recognized by their erosional base, abundant mud clasts and organic matter, and upward-fining grain-size trend. The fluid mud is commonly observed at the base of distributary channels (Ichaso and Dalrymple, 2009). The cross-stratified sandstone in the lower part of the distributary channel represents the results of the peak discharge of river floods. The upper heterolithic deposits are the results of flooding–interflooding alternations (Ichaso and Dalrymple, 2014). It alternates between the high-energy sandy deposits (thick sandstone deposits with current ripples or cross-beds) and muddier and more bioturbated deposits (bipolar rippled sandstone and bioturbated mudstone). The presence of double mud drapes and bidirectional current ripples indicates tidal rework during an interflood period.

Wave and Tidal Influence on the River-Dominated Delta—Even though the river floods (hundreds of years time scale) are the main building process of the river-dominated distributary-channel and delta-front deposits, waves, storms, and tides (daily to yearly time scale) (1) rework the channel and delta-front deposits during interflood periods, when the strength of river currents is diminished (e.g., Peng et al., 2020) and (2) modify the distal reaches of the delta-front and interdistributary embayments where the river floods have lesser effects. The wave and tidal influence are not considered dominant processes here because they are not strong enough to overcome the river processes during floods (Dalrymple et al., 2015; Kurcinka et al., 2018). This is the major point of

contrast when comparing river-dominated deltas to wave- and tide-dominated deltas.

Wave influence on river-dominated deltaic environments is recorded in the prodelta to delta-front environments, the distal mouth-bar deposits, and the interdistributary embayment environments. Wave-ripple laminated, very-fine-grained sandstones in the prodelta and interdistributary embayments are commonly the result of wave actions (Elliott, 1975) (Figures 5, 6, 9). However, this wave influence is mostly modified or replaced by bioturbation through time. Rare storm beds (HCS deposits) are also observed in river-dominated delta-front and mouth-bar deposits. Similar observations have been made in the Turonian Wall Creek Member of the Frontier Formation in the Powder River Basin (Gani and Bhattacharya, 2007), in the Lower Jurassic Tilje Formation in offshore Norway (Ichaso and Dalrymple, 2014; Ichaso et al., 2016), and the delta lobes of the Orinoco River, where there is mixed river and wave influence (Peng et al., 2020).

Tidal signals are observed both on the delta-front (in mouth-bar deposits) and on the delta-plain (in distributary channel deposits). This is due to the commonly enhanced tidal prisms that occur at river mouths as tidal waves propagate upriver (Kurcinka et al., 2018) and the fact that tidally influenced channels tend to take fine-grained sandy sediments farther out—even beyond the delta-front—than channels where tidal influence is minimal (Rossi et al., 2016). Some of these features have been well documented in the Maastrichtian Drumheller Member of the Horseshoe Canyon Formation in Alberta (Ainsworth et al., 2016) and in the fluvio-tidal channels of the Campanian Neslen Formation that feed Sego Sandstone shorelines in Utah (Olariu et al., 2015). The upward-coarsening, lower mouth-bar deposits of the Wilcox Group show heterolithic alternation of ripple-laminated fine- to medium-grained sandstone and siltstone to lower fine-grained sandstone. The sandstone-rich intervals show unidirectional ripples, some with local, underlying erosional scours probably created during flooding events. The finer sediments present bidirectional ripples and tidal rhythmites with sparse to moderate bioturbation ($BI = 0\text{--}3$), interpreted as interflood deposits (Kurcinka et al., 2018). The tidal signals in such deposits show up best during the waning flood stages or when the tidal prism is large compared to river discharge

(Dalrymple et al., 2015). Even in microtidal conditions, tidal rhythmites can be developed, especially in prodelta areas where river currents are rare (Williams, 1991; Shaw et al., 2013). The distributary channel bars are composed of fine- to medium-grained basal sandstones that overlie heterolithic strata and mudstone. The lower sandstone likely represents the peak stage of river flooding. The upward fining and thinning of this succession represent the waning discharge from the supplied river. The upper heterolithics and mudstone slowly fill the channel when the tide becomes more active and the river currents become weak (Figure 9H), during either abandonment of the channel or subsequent initial transgression.

Fluvial Channel Deposits

The upward-fining, channel-fill deposits are 5–30 ft (1.5–9.1 m) thick and commonly truncate the underlying regressive delta-front deposits (Figures 5, 10–12). The lowermost interval above the basal channel erosive surface commonly contains mud rip-up clasts (<1 in. [0.0254 m]) or subangular to subrounded pebbles (up to 5 in. [0.127 m]) (Figure 11D). The sandstone is poorly to moderately sorted and organic rich. The dominant sedimentary structures are high-angle planar or trough cross-stratification (Figure 11A, E, F). Grain size can be as large as upper-medium but mostly ranges from upper-fine to lower-medium and transitions upward to very fine grained (Figure 11). Isolated mud drapes are present within the sandstone, especially in the upper levels (Figure 11C). The flat or irregular-shaped mud drapes are <1 in. (<0.025 m) thick. However, no clear double mud drapes are observed. Wood fragments, logs, and coal layers are present. Bioturbation is rare (BI = 0–1), and only *Ophiomorpha* and *Paleophycus* are found occasionally.

This facies association is interpreted as fluvial channels because of its coarse grain size, fining-upward grain-size trend, limited-to-absent bioturbation, and abundance of coal and wood fragments and pebble-sized material. The alternation of finer-grained and coarser-grained sandstone layers within the cross-strata indicates that the in-channel dunes migrated with seasonal variations in river flooding. The presence of mud drapes and bioturbation in some of the channels suggests proximity to the river mouth and more

marine and tidal influence, especially during interflood periods.

Transgressive Intervals

Fluvio-Tidal, Inner to Middle Estuarine Deposits

This association is characteristically overall upward-fining in grain size at a scale of 3 to 300 ft (meters to tens of meters). It transitionally or sharply overlies the fluvial channel deposits described in the Fluvial Channel Deposits section or sometimes directly overlies regressive delta-front deposits (Figures 5, 10–12). Small-scale (several feet), irregularly upward-fining intervals—each with mud clasts or conglomerates as a base—stack vertically with one another to form successions that are tens of feet in scale. The upward transition from the underlying fluvial channel deposits can be easily recognized by the increasing amounts of mud drapes and bioturbation (Figures 11, 12). The mud drapes are more frequent (sometimes as double mud drapes) than those in the fluvial channels (Figures 11H, I). Fine- to medium-grained sandstones of this association typically occur as high-angle cross-stratified sets (locally bidirectional; Figure 11G) or in mud-draped and bidirectional ripple-laminae. The sandstone is moderately to well sorted and organic rich. Unbioturbated and unlaminated fluid mud layers can be observed between some of the sandy beds. Rare *Ophiomorpha*, *Skolithos*, *Paleophycus*, and *Planolites* are also present. The heterolithic deposits are dominated by very-thin-bedded siltstones and very-fine- to lower-fine-grained sandstones that alternate with dark mudstones as in flaser, wavy, and lenticular bedded facies (Figure 11J), sometimes with bidirectional ripples. The thickness of each bed varies from 0.5 to 5.0 in. (0.0127–0.127 m). Bioturbation is moderate to pervasive and commonly present in the mudstone and siltstone with *Chondrites*, *Thalassinoides*, *Planolites*, *Paleophycus*, and *Asterosoma*. These trace fossils are small, measuring only up to 2 in. (5.1 cm).

The small-scale fining-upward, cross-stratified sandstone units are interpreted as the infilling of individual fluvio-tidal channels that resulted from interacting fluvial and tidal (ebb and flood) currents. The larger-scale composite sandstone units are interpreted as stacked sets of dunes and compound dunes forming tidal bars (Olariu et al., 2012). These bars were either partially eroded by other channels or filled with bioturbated heterolithic deposits. The

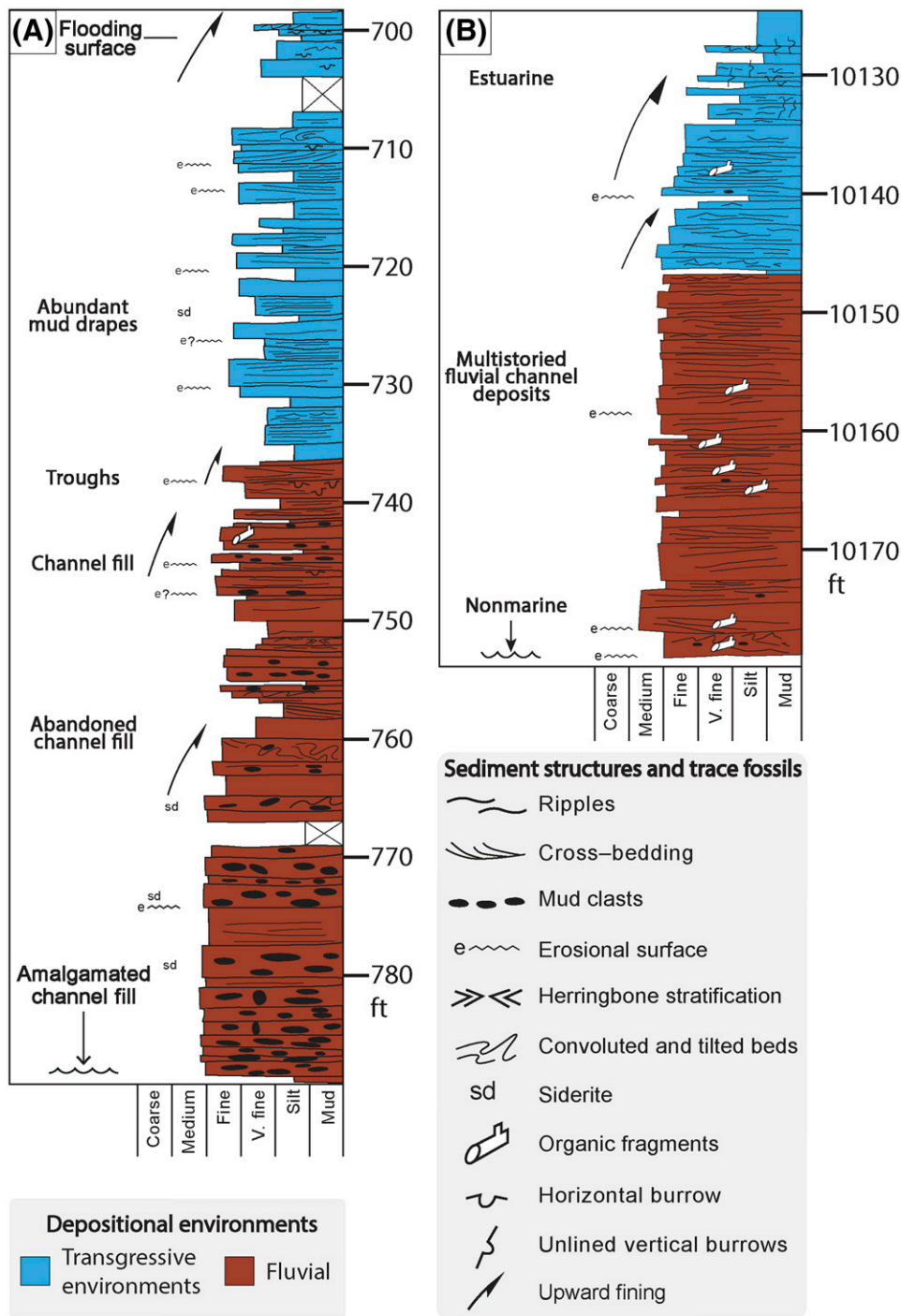


Figure 10. Examples of overall transgressive transition from fluvial to fluvio-tidal deposits: (A) 700–790 ft of Letco TOH-2A Settlemyre; (B) 10,125–10,180 ft of Vogelsang 1 Frieda. V. fine = very fine.

presence of rhythmic mud drapes, fluid mud, and bidirectional paleocurrents in the sandy intervals strongly suggests a stronger tidal influence than that in the underlying regressive deltas. The presence of fluid mud layers and sharp bases associated with

rip-up mud clasts indicates thalweg infill of the channels (Ichaso and Dalrymple, 2009). The upward transition to bioturbated heterolithic deposits and the frequent bidirectional paleocurrents suggest a relatively low-energy environment influenced by tidal

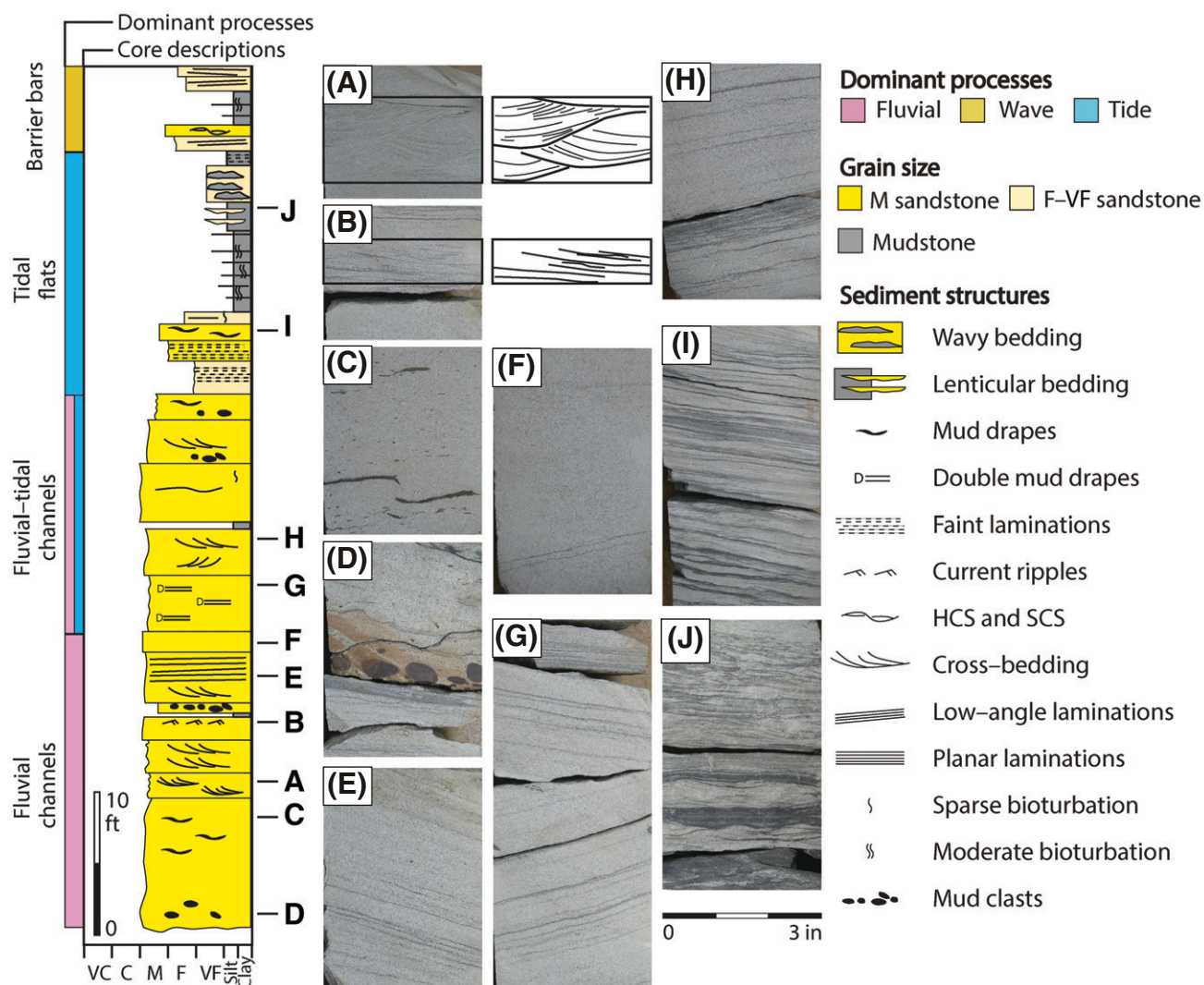


Figure 11. Fluvial and estuarine deposits. Left: Facies succession of fluvial and estuarine deposits with fluvial, tidal, and wave influence and locations of core photographs. Right: (A) Fine-grained (F) sandstone with trough cross-beds; (B) F sandstone with current ripples; (C) F sandstone with broken mud drapes; (D) sharp-based F sandstone with mud clasts; (E) cross-bedded F sandstone; (F) structureless F sandstone; (G) bidirectional cross-bedded F sandstone with possible double mud drapes; (H) cross-bedded F sandstone; (I) heterolithic bedding with current ripples; and (J) heterolithic bedding with wavy ripples. C = coarse; HCS and SCS = hummocky and swaley cross-stratification; M = medium; VC = very coarse.

processes. The pattern of bioturbated mudstone to siltstone and rippled siltstone to sandstone is interpreted as tidal rhythmites recording repetitive tidal cycles within quite ponded environments or in areas of ripple or dune movement. The overall increasing mud content and decreasing thickness of sandstone beds upward in these successions suggest a general shoreline retreat landward, with muddy central basin deposits developing on top of the older estuary distributary channels. The organic-rich mudstone and coal layers represent interfingering with a fringing, supratidal flat area. Bioturbation from a restricted

ichnofauna suggests an overall brackish water inner to middle estuary environment. These relatively muddy deposits are commonly overlain by the outer estuary deposits introduced in the Barrier-Fronted, Wave-Dominated, Outer Estuary Deposits section.

Barrier-Fronted, Wave-Dominated, Outer Estuary Deposits

This facies association is also overall upward-fining, is up to a few tens of feet thick, and occurs in the topmost interval of the transgressive half-cycle (i.e., just below the MFS) (Figure 11). It is the

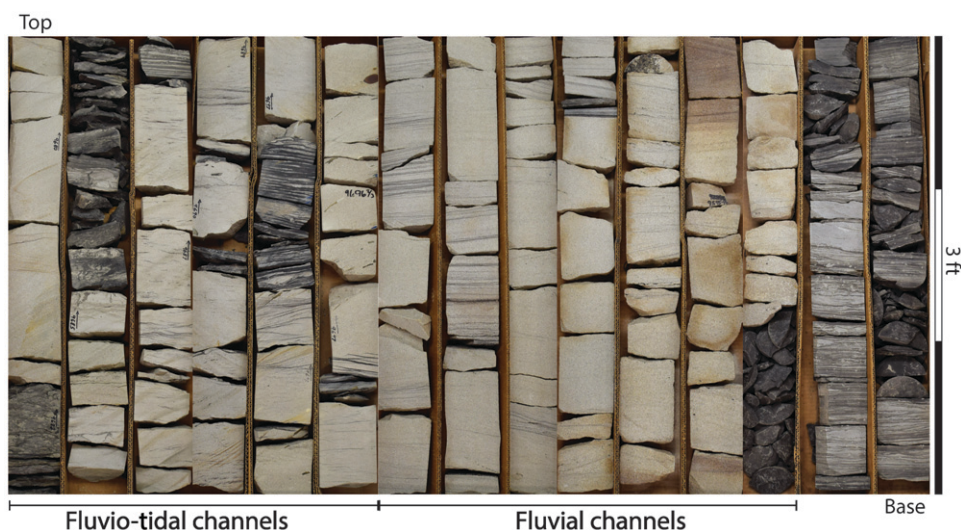


Figure 12. Photographs showing the transition from fluvial channel deposits to fluvio-tidal channel deposits. The abundance of mud laminae increases upward. Muddy tidal rhythmites are present in the upper parts of the successions.

muddiest and most bioturbated interval within the transgressive half-cycle. The lower part is composed of alternating dark mudstones and very-fine-grained sandstones, displaying flaser, wavy, and lenticular bedded facies. The proportion of mudstone increases upward, including thick, highly bioturbated organic-rich mudstone and thin, locally present coals. In some cases, the muddy heterolithics are overlain by a 5- to 8-ft-thick (1.5–2.4 m), upward-coarsening interval. The upward-coarsening interval is interbedded bioturbated mudstone to siltstone and very-fine- to fine-grained sandstone with HCS and SCS, low-angle laminations, and sometimes trough cross-beds. The mudstones and siltstones in this association are bioturbated by *Cruziana* and *Skolithos* ichnofacies such as *Thalassinoides*, *Planolites*, *Paleophycus*, *Teichichnus*, *Skolithos*, and *Ophiomorpha*. The sandstone is clean and locally organic rich.

Highly bioturbated, heterolithic deposits with bidirectional ripples likely represent a restricted, tide-dominated environment. They can be formed in sheltered areas at the estuary mouth, such as in the central mud basin typical of wave-dominated estuaries. The sandy upward-coarsening intervals are likely remnants of the lowermost preserved portion of a barrier bar, which typically shelters the mud basin behind it. Flaser, wavy, or lenticular beds with alternating mudstone, siltstone, and sandstone suggest an intertidal setting, whereas the bioturbated mudstones and coal layers could represent surrounding supratidal areas of

marsh grass. The repetitive siltstone and mudstone layers are interpreted as tidal rhythmites, which are caused by seasonal variations in river discharge into the head area of the mud basin and are modulated by frequent tidal cycles (Dalrymple, 2010; Dalrymple et al., 2015; Gugliotta et al., 2015). The occasional overlying sandy upward-coarsening unit (Figure 11) is interpreted as a preserved landward-migrating transgressive barrier stacked on top of restricted mud-basin deposits. However, the transgressive shoreface deposits show a general upward-fining succession, in contrast to the general upward-coarsening grain-size trend in regressive shoreface. The transgressive barrier-bar and shoreface deposits are only present in wave-dominated estuaries and are not commonly observed because many of them are eroded during transgression (Dalrymple, 1992).

CHARACTERISTICS OF THE TOPSET T-R CYCLES IN VOGELSANG 1 FRIEDA AND LETCO TOH-2A SETTLEMIRE CORES

As described and interpreted above, each T-R cycle consists of prograding, wave-influenced shoreline, fluvial deposits, and then tidal-estuarine deposits; however, some cycles do not have all three intervals present. The Vogelsang 1 Frieda and Letco TOH-2A Settlemyre cores allow stacks of 14 and 11 such cycles, respectively, to be distinguished (Figures 2–4).

The durations of the lower Wilcox strata and middle Wilcox deposition are 4.2 and 3.3 m.y., respectively (Galloway et al., 2011). Therefore, the estimated duration of each cycle in the Vogelsang 1 Frieda core is <300 k.y., whereas that of the Letco TOH-2A Settlemyre core is <680 k.y. The cycle duration in Letco TOH-2A Settlemyre is likely overestimated due to an amalgamation of T-R cycles or uncertainty in the lowermost muddy part of core. The proximal location of the Letco TOH-2A Settlemyre well, indicated by the high proportion of delta-plain deposits

and finer grain sizes, would have favored amalgamation and a lack of marine transgressions reaching this landward location. Incomplete preservation of T-R cycles can be caused by (1) depocenter switching, causing delta lobes to thin out laterally; (2) bypass to distal locations; and (3) channel downcutting eroding underlying deposits, thus amalgamating fluvial sandstones.

The T-R cycles in Vogelsang 1 Frieda range in thickness from 63 to 303 ft (19.2–92.4 m), with a mean of 159 ft (48.5 m) (Figure 13). The mean

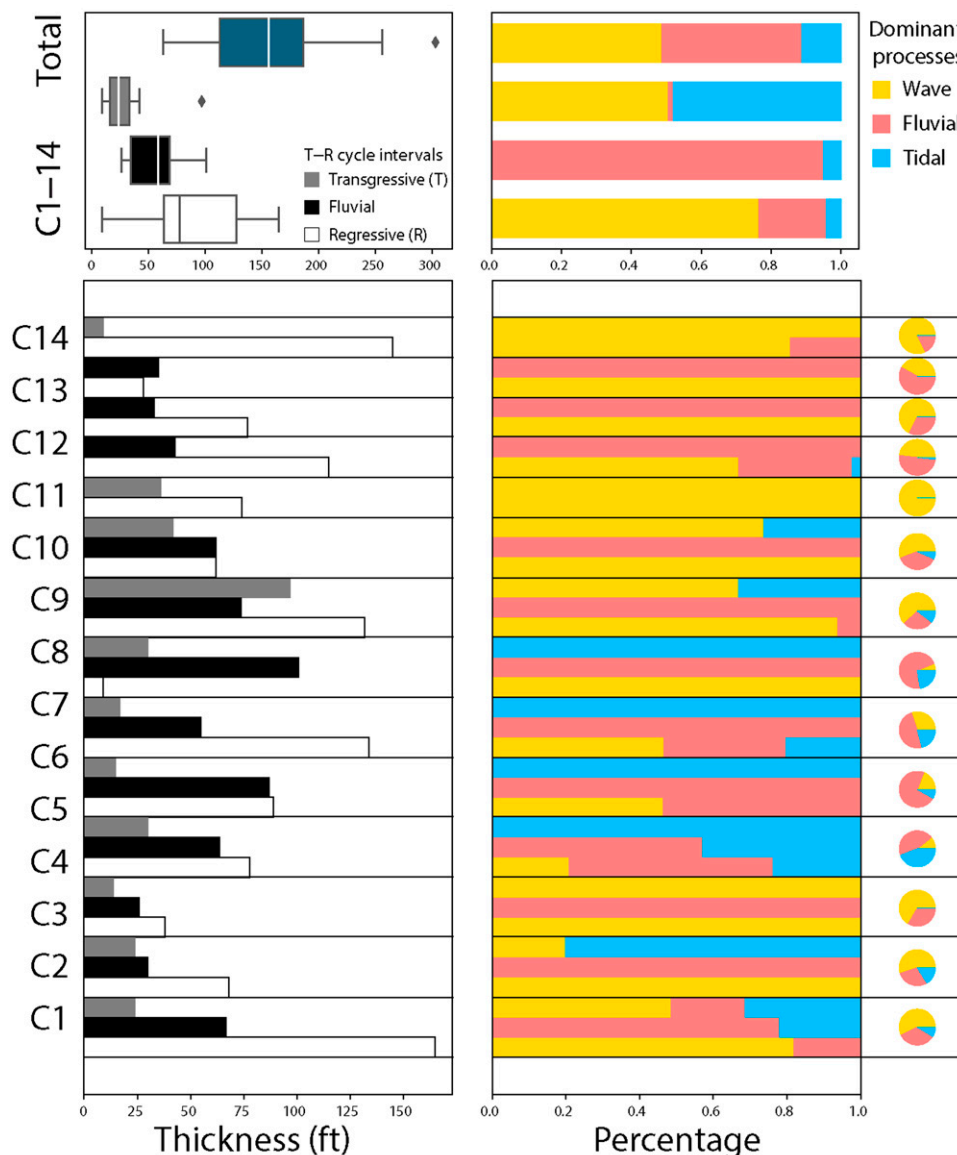


Figure 13. Thickness variations and process percentages (wave, river, tide) of regressive, fluvial, and transgressive intervals for 14 cycles of Vogelsang 1 Frieda cores. The upper half of the figure shows the data for all of the cycles, and the lower half shows the data within each cycle. C1–C14 = cycle number 1–14.

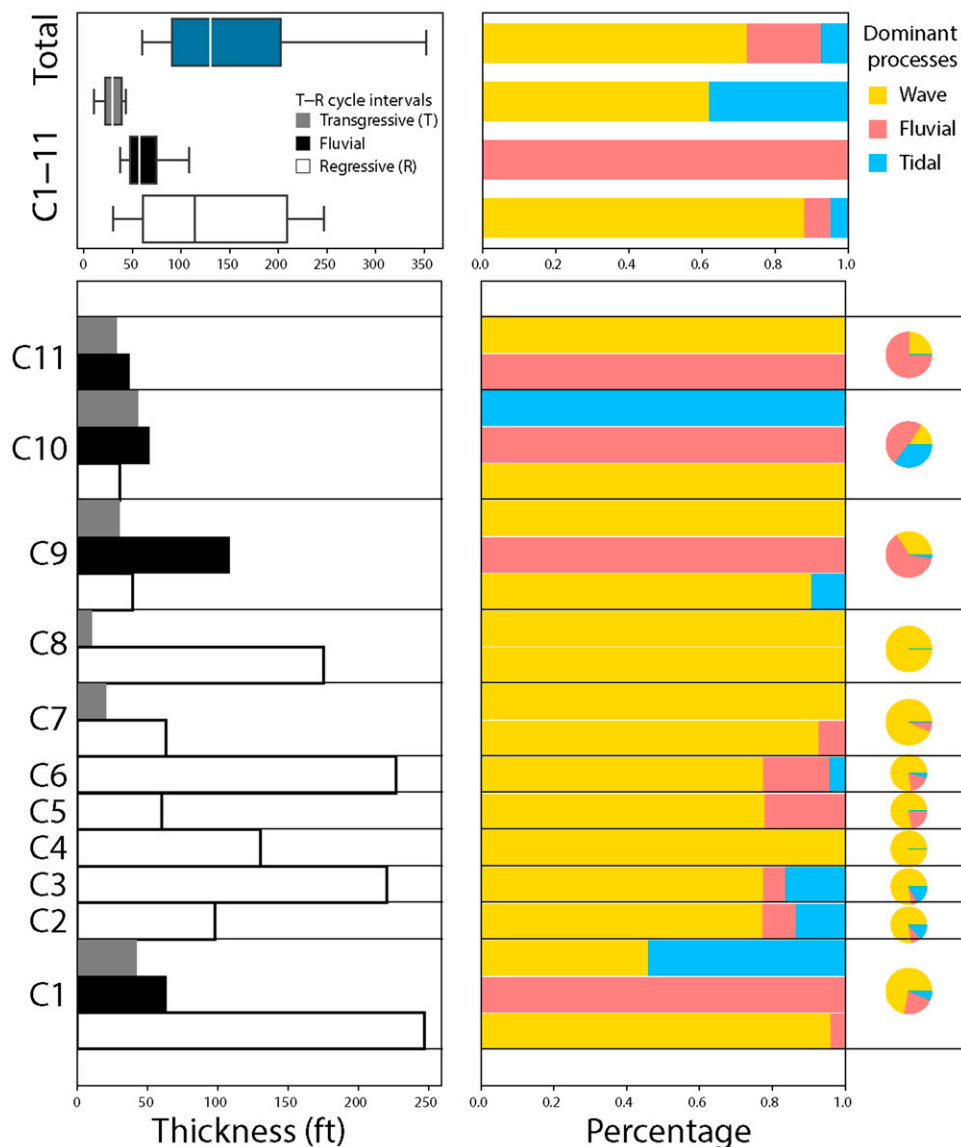


Figure 14. Thickness variations and process percentages (wave, river, tide) of regressive, fluvial, and transgressive intervals for 11 cycles of Letco TOH-2A Settlemyre. The upper half of the figure shows the data for all of the cycles, and the lower half shows the data within each cycle. C1–C11 = cycle number 1–11.

thickness of regressive shoreline intervals is 87 ft (26.5 m), 56 ft (17.1 m) for fluvial intervals, and 31 ft (9.4 m) for estuarine intervals. The T-R cycles in Letco TOH-2A Settlemyre vary in thickness from 60 to 352 ft (18.3–107.3 m), with a mean of 156 ft (47.5 m) (Figure 14). The mean thickness of regressive, fluvial, and estuarine intervals decreases from 129 to 65 to 29 ft (39.3 to 19.8 to 8.8 m). The maximum thickness of shoreface or delta-front units correlates to the water depth, which itself is controlled by the amplitude of relative sea-level changes (Sømme et al., 2009), whereas the thickness of fluvial channels

is related to the magnitude of sediment discharge and water discharge (Blum et al., 2013; Milliken et al., 2018). The similar ranges (63–303 ft versus 60–352 ft) (19.2–92.4 versus 18.3–107.3 m) and mean thickness (159 ft versus 156 ft) (48.5 m versus 47.5 m) of T-R cycles in the two cores is due to both wells cutting the same deltaic system and both environments being controlled by the same greenhouse sea-level changes.

The regressive delta-front intervals in both cores are either wave-dominated or river-dominated (Figures 13, 14). Wave, fluvial and tidal signals in the regressive intervals occur at 72%, 21%, and 7%

in Vogelsang 1 Frieda and 77%, 19%, and 4% in Letco TOH-2A Settlemyre. The fluvial intervals of cycles 1 and 4 in Vogelsang 1 Frieda are composed of fluvio-tidal channels (Figure 13); this is why 5% of the fluvial interval in Vogelsang 1 Frieda core is influenced by tides. The transgressive intervals of both cores are dominated by wave (51% in Vogelsang 1 Frieda and 62% in Letco TOH-2A Settlemyre) and tidal processes (48% in Vogelsang 1 Frieda and 38% in Letco TOH-2A Settlemyre) (Figures 13, 14).

DISCUSSION: PROCESS VARIABILITY AT DIFFERENT TIME SCALES

This work clearly documents the presence of >10 T-R cycles in the Paleogene topset of the study area of the Gulf of Mexico margin, indicating that the multimillion-year interval is not composed of one giant deltaic system or even multiple simple progradational systems. Instead, at the time scale of hundreds of thousands of years, both the Vogelsang 1 Frieda and Letco TOH-2A Settlemyre cores show that there was repetitive cross-shelf transit of deltas showing a T-R cycle with intervening distributary channels, thus providing evidence of repeated, long-distance T-R shoreline migration on the Paleogene shelf, even during low-amplitude, low-frequency greenhouse sea-level changes (Zhang et al., 2016). Each interval (i.e., regressive, fluvial, or transgressive) ranges from several feet to hundreds of feet thick. The T-R cycle is 60–352 ft (18.3–107.3 m) thick. This range of spatial scales (Figures 13, 14) will be useful for identifying T-R cycles in other settings with similar high supplies of sediments and greenhouse sea-level changes.

Process Transition between Regressive, Fluvial, and Transgressive Intervals

A detailed paleo-environmental analysis on ~4000 ft (~1200 m) of core shows that the process mix and the dominant process (wave, fluvial, or tidal currents) varied frequently across different time scales (Figure 15). At a time scale less than that of basic T-R cycles (less than a few hundred thousand years), the transition zones between regressive, fluvial, and transgressive intervals of any cycle reflect the short time scale of

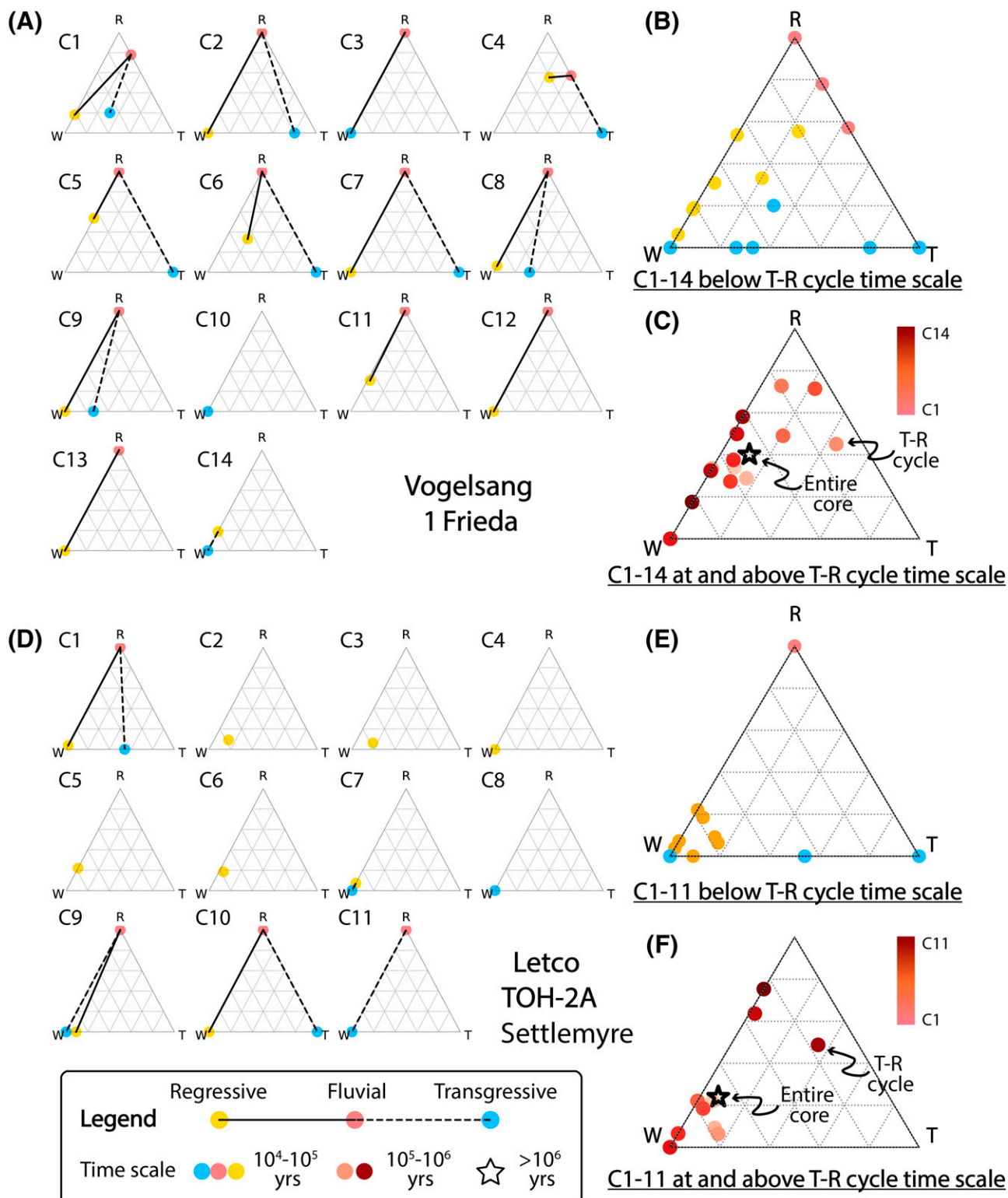
changes in the dominant process (Figure 15A, D). The regressive interval of the basic cycle is either wave dominated or river dominated. The fluvial intervals reflect a dominance of fluvial or fluvio-tidal influence. The transgressive intervals show only weak river currents and are dominated by wave or tidal signals. The thickness of the transition zone between changes in dominant process varies for each cycle due to the different makeup of regressive, fluvial, and transgressive intervals; however, it should be noted that the time changes were observed only in a 1-D profile.

Processes at Basic Cycle Time Scale

At the time scale of T-R cycles (approximately a few hundred thousand years, tens to hundreds of feet thick), the dominant processes are the average values of the process signals seen across both shallow-marine (i.e., regressive and transgressive shorelines) and fluvial systems. This work shows that the T-R cycles of the Vogelsang 1 Frieda and Letco TOH-2A Settlemyre cores are dominated by either wave or fluvial processes (Figures 15C, F).

Lower-Frequency Process Changes

Some changes in process dominance occur at a frequency lower than that of the T-R cycles (more than hundreds of thousands of years, hundreds to thousands of feet thick), seen by the stacking of cycles, with process changes reflected by the average process values across multiple T-R cycles. However, at this scale, the changes may simply represent broader proximal-distal changes related to the basinward or landward migration of the larger Wilcox clastic wedges. Vogelsang 1 Frieda is composed of 48% wave-dominated deposits, 40% river-dominated deposits, and 12% tide-dominated deposits. Letco TOH-2A Settlemyre is composed of 69% wave-dominated deposits, 24% river-dominated deposits, and 7% tide-dominated deposits (Figure 15C, F). The percentage of the dominant processes below the time scale of the T-R cycle has geological meaning, whereas that at or above the time scale of the T-R cycle is the average value over a longer time scale and has only a statistical meaning. The former indicates the process variability of regressive or transgressive shorelines, which defines shoreline type and controls



shoreline morphology and sandstone thickness geometry (Ainsworth et al., 2011; Rossi et al., 2015).

CONCLUSIONS

1. Detailed analyses of the 2240-ft (682.8-m) Vogelsang 1 Frieda core and the 1730-ft (527.3-m) Letco TOH-2A Settlemyre core show that the Paleogene Wilcox succession is composed of at least 11–14 T-R cycles in this region of the Gulf of Mexico margin topset. Each cycle is distinct and has a maximum duration of 300–680 k.y. One complete T-R cycle records the seaward to landward cross-shelf transit of the shoreline supply system, expressed vertically in the cores from a regressive deltaic interval to a fluvial interval to a transgressive estuarine interval. The thickness of T-R cycles ranges from 60 to 352 ft (18.3 to 108.3 m). The average thicknesses of the T-R cycles in Vogelsang 1 Frieda and Letco TOH-2A Settlemyre are 159 and 156 ft (48.5 and 47.5 m), respectively.
2. The Wilcox regressive deltas were either wave dominated or river dominated and range from 9 to 247 ft (2.7 to 75.3 m) thick when they passed across the core location. Wave-dominated deltaic deposits also show an influence of tidal and fluvial processes. The tide influence within the shoreface deposits is detected by thick (>0.5 ft) (>0.15 m) bidirectional current-rippled sandstone beds. Mud-draped sandstone, sometimes double mud drapes, are also observed within clean storm-generated beds and fair-weather beds. Current ripples and mud drapes are seldom observed in purely wave-dominated environments and are interpreted as having been created by tidal flux between storm events or within the waning stages of storm events (Dashtgard et al., 2012; Wei et al., 2016). The fluvial influences can be detected by the presence of graded or structureless siltstone, which transitions to very-fine-grained sandstone beds with abundant organic matter, and these are interpreted as hyperpycnites associated with river flooding. Within the river-dominated deltas with mouth-bar deposits, wave and tidal processes can rework the channel and delta-front deposits during interflood periods and they also tend to modify the lower delta front and the associated interdistributary embayment environments.
3. Fluvial intervals occurring in the vertical transition from regressive to transgressive half-cycles are composed of fluvial channels and fluvial-tidal channels, which truncate the underlying regressive deposits. The intervals are between 26 and 108 ft (7.9 and 32.9 m) thick and are sometimes composed of stacked channel deposits. The transgressive interval, ranging from 9 to 97 ft (2.7 to 29.6 m) thick, is composed of estuarine and barrier-bar deposits, which are dominated by wave and tidal processes.
4. The sedimentological analysis of process mixing up through the ~ 4000 ft (~ 1200 m) of core indicates that the dominant processes change frequently across different time scales. At or below the time scale of T-R cycles (less than hundreds of thousands of years), the cycles of Vogelsang 1 Frieda and Letco TOH-2A Settlemyre cores exhibit an upward change from regressive, wave-dominated, or river-dominated delta deposits to fluvial and fluvial-tide channel deposits and then to wave- or tide-dominated transgressive deposits. At or above the time scale of T-R cycles (approximately or more than hundreds of thousands of years), the reported dominant process is the average value recorded from one or multiple T-R cycles, and it therefore carries little geological meaning. The individual stratigraphic cycles of Vogelsang 1 Frieda and the 1730-ft (527.3-m) Letco TOH-2A Settlemyre are either wave or river dominated at a time scale of approximately hundreds of thousands of years. At the million-years time scale, the entire Vogelsang 1 Frieda core is 48% wave-dominated deposits, 40% river-dominated deposits, and 12% tide-dominated deposits, whereas the entire Letco TOH-2A Settlemyre core is 69% wave-dominated deposits, 24% river-dominated deposits, and 7% tide-dominated deposits (Figures 15C, F).
5. This work provides depositional models for T-R shelf-transit cycles within the Wilcox Group, Gulf of Mexico, based on ~ 4000 ft (~ 1200 m) of core descriptions. It shows that the dominant processes (fluvial, wave, tidal) change frequently at time scales below hundreds of thousands of years, showing that it is an oversimplification to refer, for example, to the 4.2-m.y. lower Wilcox

Formation as a single delta. The reported spatial scales of regressive, fluvial, and transgressive intervals (Figures 13, 14), summarized from 25 T-R cycles, illustrate how a thick shallow-water succession should be subdivided to construct the stratigraphic framework, thereby demonstrating the nature of the fundamental T-R building blocks also relevant in other similar high-supply, greenhouse shelf settings.

REFERENCES CITED

- Ainsworth, R. B., B. K. Vakarelov, J. A. MacEachern, R. A. Nanson, T. I. Lane, F. Rarity, and S. E. Dashtgard, 2016, Process-driven architectural variability in mouth-bar deposits: A case study from a mixed-process mouth-bar complex, Drumheller, Alberta, Canada: *Journal of Sedimentary Research*, v. 86, no. 5, p. 512–541, doi:[10.2110/jsr.2016.23](https://doi.org/10.2110/jsr.2016.23).
- Ainsworth, R. B., B. K. Vakarelov, J. A. MacEachern, F. Rarity, T. I. Lane, and R. A. Nanson, 2017, Anatomy of a shoreline regression: Implications for the high-resolution stratigraphic architecture of deltas: *Journal of Sedimentary Research*, v. 87, no. 5, p. 425–459, doi:[10.2110/jsr.2017.26](https://doi.org/10.2110/jsr.2017.26).
- Ainsworth, R. B., B. K. Vakarelov, and R. A. Nanson, 2011, Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: Toward improved subsurface uncertainty reduction and management: *AAPG Bulletin*, v. 95, no. 2, p. 267–297, doi:[10.1306/06301010036](https://doi.org/10.1306/06301010036).
- Ambrose, W., H. Zeng, M. Olariu, and J. Zhang, 2018, Depositional history and shoreline evolution of the Upper Wilcox Group and Lower Reklaw Formation, Northern Bee County, Texas: Austin, Texas, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 284, 87 p.
- Bebout, D. G., B. R. Weise, A. R. Gregory, and M. B. Edwards, 1982, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast: Their potential for production of geopressured geothermal energy: Austin, Texas, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 117, 125 p.
- Bhattacharya, J. P., and R. G. Walker, 1991, River- and wave-dominated depositional systems of the Upper Cretaceous Dunvegan Formation, northwestern Alberta: *Bulletin of Canadian Petroleum Geology*, v. 39, p. 165–191.
- Bhattacharya, J. P., and J. A. MacEachern, 2009, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: *Journal of Sedimentary Research*, v. 79, no. 4, p. 184–209, doi:[10.2110/jsr.2009.026](https://doi.org/10.2110/jsr.2009.026).
- Blum, M., J. Martin, K. Milliken, and M. Garvin, 2013, Paleovalley systems: Insights from Quaternary analogs and experiments: *Earth-Science Reviews*, v. 116, p. 128–169, doi:[10.1016/j.earscirev.2012.09.003](https://doi.org/10.1016/j.earscirev.2012.09.003).
- Boyd, R., R. Dalrymple, and B. A. Zaitlin, 1992, Classification of clastic coastal depositional environments: *Sedimentary Geology*, v. 80, no. 3–4, p. 139–150, doi:[10.1016/0037-0738\(92\)90037-R](https://doi.org/10.1016/0037-0738(92)90037-R).
- Burgess, P. M., and N. Hovius, 1998, Rates of delta progradation during highstands: Consequences for timing of deposition in deep-marine systems: *Journal of the Geological Society*, v. 155, no. 2, p. 217–222, doi:[10.1144/gsjgs.155.2.0217](https://doi.org/10.1144/gsjgs.155.2.0217).
- Cross, T. A., C. K. Wilgus, B. S. Hastings, H. Posamentier, J. V. Wagoner, C. A. Ross, and C. G. S. C. Kendall, 1988, Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, Western Interior, U.S.A, in C. K. Wilgus, B. S. Hastings, H. W. Posamentier, J. C. Van Wagoner, C. A. Ross, and C. G. S. C. Kendall eds., *Sea-level changes: An integrated approach*: Tulsa, Oklahoma, SEPM Special Publication 42, p. 371–380, doi:[10.2110/pec.88.01.0371](https://doi.org/10.2110/pec.88.01.0371).
- Dalrymple, R. W., 1992, Tidal depositional systems, in R. G. Walker and N. P. James, eds., *Facies models response to sea-level change*: St. John's, Newfoundland, Geological Association of Canada, 195–218.
- Dalrymple, R. W., 2010, Interpreting sedimentary successions: facies, facies analysis and facies models: *Facies Models*, v. 4, p. 3–18.
- Dalrymple, R. W., C. E. Kurcinka, B. V. J. Jablonski, A. A. Ichaso, and D. A. Mackay, 2015, Deciphering the relative importance of fluvial and tidal processes in the fluvial-marine transition, in P. J. Ashworth, J. L. Best, and D. R. Parsons, eds., *Fluvial-tidal sedimentology*: New York, Elsevier, *Developments in Sedimentology* 68, p. 3–45, doi:[10.1016/B978-0-444-63529-7.00002-X](https://doi.org/10.1016/B978-0-444-63529-7.00002-X).
- Dashtgard, S. E., J. A. MacEachern, S. E. Frey, and M. K. Gingras, 2012, Tidal effects on the shoreface: Towards a conceptual framework: *Sedimentary Geology*, v. 279, p. 42–61, doi:[10.1016/j.sedgeo.2010.09.006](https://doi.org/10.1016/j.sedgeo.2010.09.006).
- Dixon, J. F., R. J. Steel, and C. Olariu, 2013, A model for cutting and healing of deltaic mouth bars at the shelf edge: Mechanism for basin-margin accretion: *Journal of Sedimentary Research*, v. 83, no. 3, p. 284–299, doi:[10.2110/jsr.2013.25](https://doi.org/10.2110/jsr.2013.25).
- Edwards, M. B., 1980, Live Oak Delta Complex—Unstable, shelf-edge delta in deep Wilcox trend of South Texas: *AAPG Bulletin*, v. 64, p. 1556–1557, doi:[10.1306/2F919602-16CE-11D7-8645000102C1865D](https://doi.org/10.1306/2F919602-16CE-11D7-8645000102C1865D).
- Edwards, M. B., 1981, Upper Wilcox Rosita Delta system of South Texas: Growth-faulted shelf-edge deltas: *AAPG Bulletin*, v. 65, p. 54–73, doi:[10.1306/2F91976F-16CE-11D7-8645000102C1865D](https://doi.org/10.1306/2F91976F-16CE-11D7-8645000102C1865D).
- Elliott, T., 1975, The sedimentary history of a delta lobe from a Yoredale (carboniferous) cyclothem: *Proceedings of the Yorkshire Geological Society*, v. 40, no. 4, p. 505–536, doi:[10.1144/pygs.40.4.505](https://doi.org/10.1144/pygs.40.4.505).
- Embry, A. F., 1995, Sequence boundaries and sequence hierarchies: Problems and proposals, in R. J. Steel, V. L. Felt, E. P. Johannessen, and C. Mathieu, eds., *Sequence stratigraphy on the northwest European margin*: New York, Elsevier, *Norwegian Petroleum Society Special Publication* 5, p. 1–11, doi:[10.1016/S0928-8937\(06\)80059-7](https://doi.org/10.1016/S0928-8937(06)80059-7).

- Embry, A. F., 2002, Transgressive-regressive (T-R) sequence stratigraphy, in J. M. Armentrout and N. C. Rosen, eds., Sequence stratigraphic models for exploration and production: Evolving methodology, emerging models and application histories: Tulsa, Oklahoma, SEPM, p. 151–172, doi:[10.5724/gcs.02.22](https://doi.org/10.5724/gcs.02.22).
- Embry, A. F., and E. P. Johannessen, 1993, T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic–Lower Jurassic succession, western Sverdrup Basin, Arctic Canada, in T. O. Vorren, E. Bergsager, Ø. A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, and T. B. Lund, eds., Arctic geology and petroleum potential: New York, Elsevier, Norwegian Petroleum Society Special Publication 2, p. 121–146, doi:[10.1016/B978-0-444-88943-0.50013-7](https://doi.org/10.1016/B978-0-444-88943-0.50013-7).
- Fisher, W. L., and J. H. McGowen, 1969, Depositional systems in Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas: AAPG Bulletin, v. 53, no. 1, p. 30–54, doi:[10.1306/5D25C591-16C1-11D7-8645000102C1865D](https://doi.org/10.1306/5D25C591-16C1-11D7-8645000102C1865D).
- Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis II: Application to Northwest Gulf of Mexico Cenozoic Basin: AAPG Bulletin, v. 73, no. 2, p. 143–154, doi:[10.1306/703C9AFA-1707-11D7-8645000102C1865D](https://doi.org/10.1306/703C9AFA-1707-11D7-8645000102C1865D).
- Galloway, W. E., T. L. Whiteaker, and P. Ganey-Curry, 2011, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin: Geosphere, v. 7, no. 4, p. 938–973, doi:[10.1130/GES00647.1](https://doi.org/10.1130/GES00647.1).
- Gani, M. R., and J. P. Bhattacharya, 2007, Basic building blocks and process variability of a cretaceous delta: Internal facies architecture reveals a more dynamic interaction of river, wave, and tidal processes than is indicated by external shape: Journal of Sedimentary Research, v. 77, no. 4, p. 284–302, doi:[10.2110/jsr.2007.023](https://doi.org/10.2110/jsr.2007.023).
- Gugliotta, M., S. S. Flint, D. M. Hodgson, and G. D. Veiga, 2015, Stratigraphic record of river-dominated crevasse subdeltas with tidal influence (Lajas Formation, Argentina): Journal of Sedimentary Research, v. 85, no. 3, p. 265–284, doi:[10.2110/jsr.2015.19](https://doi.org/10.2110/jsr.2015.19).
- Hampson, G. J., A. B. Rodriguez, J. E. A. Storms, H. D. Johnson, C. T. Meyer, G. J. Hampson, R. J. Steel, P. M. Burgess, and R. W. Dalrymple, 2008, Geomorphology and high-resolution stratigraphy of progradational wave-dominated shoreline deposits: Impact on reservoir-scale facies architecture, in G. J. Hampson, ed., Recent advances in models of siliciclastic shallow-marine stratigraphy: Tulsa, Oklahoma, SEPM, v. 90, p. 117–142, doi:[10.2110/pec.08.90.0117](https://doi.org/10.2110/pec.08.90.0117).
- Ichaso, A. A., and R. W. Dalrymple, 2009, Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway: Geology, v. 37, no. 6, p. 539–542, doi:[10.1130/G25481A.1](https://doi.org/10.1130/G25481A.1).
- Ichaso, A. A., and R. W. Dalrymple, 2014, Eustatic, tectonic and climatic controls on an early syn-rift mixed-energy delta, Tilje Formation (Early Jurassic, Smørbukk field, offshore mid-Norway), in A. W. Martinus, R. Ravnås, J. A. Howell, R. J. Steel, and J. P. Wonham, eds., From depositional systems to sedimentary successions on the Norwegian continental margin: Chichester, United Kingdom, International Association of Sedimentologists Special Publication 46, p. 339–388, doi:[10.1002/9781118920435.ch13](https://doi.org/10.1002/9781118920435.ch13).
- Ichaso, A. A., R. W. Dalrymple, and A. W. Martinus, 2016, Basin analysis and sequence stratigraphy of the synrift Tilje Formation (Lower Jurassic), Halten terrace giant oil and gas fields, offshore mid-Norway: AAPG Bulletin, v. 100, no. 8, p. 1329–1375, doi:[10.1306/02251614081](https://doi.org/10.1306/02251614081).
- Kurcinka, C., R. W. Dalrymple, and M. Gugliotta, 2018, Facies and architecture of river-dominated to tide-influenced mouth bars in the lower Lajas Formation (Jurassic), Argentina: AAPG Bulletin, v. 102, no. 5, p. 885–912, doi:[10.1306/0609171618917155](https://doi.org/10.1306/0609171618917155).
- Lindsay, J. F., D. B. Prior, and J. M. Coleman, 1984, Distributary-mouth bar development and role of submarine landslides in delta growth, South Pass, Mississippi Delta: AAPG Bulletin, v. 68, no. 11, p. 1732–1743, doi:[10.1306/AD46198A-16F7-11D7-8645000102C1865D](https://doi.org/10.1306/AD46198A-16F7-11D7-8645000102C1865D).
- Marchand, A. M. E., G. Apps, W. Li, and J. R. Rotzien, 2015, Depositional processes and impact on reservoir quality in deepwater Paleogene reservoirs, US Gulf of Mexico: AAPG Bulletin, v. 99, no. 9, p. 1635–1648, doi:[10.1306/04091514189](https://doi.org/10.1306/04091514189).
- Miller, K. G., J. V. Browning, W. J. Schmelz, R. E. Kopp, G. S. Mountain, and J. D. Wright, 2020, Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records: Science Advances, v. 6, no. 20, eaaz1346, 15 p., doi:[10.1126/sciadv.aaz1346](https://doi.org/10.1126/sciadv.aaz1346).
- Miller, K. G., M. A. Kominz, J. V. Browning, J. D. Wright, G. S. Mountain, M. E. Katz, P. J. Sugarman, B. S. Cramer, N. Christie-Blick, and S. F. Pekar, 2005, The phanerozoic record of global sea-level change: Science, v. 310, no. 5752, p. 1293–1298, doi:[10.1126/science.1116412](https://doi.org/10.1126/science.1116412).
- Milliken, K. T., M. D. Blum, J. W. Snedden, and W. E. Galloway, 2018, Application of fluvial scaling relationships to reconstruct drainage-basin evolution and sediment routing for the Cretaceous and Paleocene of the Gulf of Mexico: Geosphere, v. 14, no. 2, p. 749–767, doi:[10.1130/GES01374.1](https://doi.org/10.1130/GES01374.1).
- Mitchum, R. M., and J. C. Van Wagoner, 1991, High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles: Sedimentary Geology, v. 70, no. 2–4, p. 131–160, doi:[10.1016/0037-0738\(91\)90139-5](https://doi.org/10.1016/0037-0738(91)90139-5).
- Mulder, T., J. P. M. Syvitski, S. Migeon, J.-C. Faugères, and B. Savoye, 2003, Marine hyperpycnal flows: Initiation, behavior and related deposits: A review: Marine and Petroleum Geology, v. 20, no. 6–8, p. 861–882, doi:[10.1016/j.marpetgeo.2003.01.003](https://doi.org/10.1016/j.marpetgeo.2003.01.003).
- Muto, T., and R. J. Steel, 2002, Role of autoretreat and A/S changes in the understanding of deltaic shoreline trajectory: A semi-quantitative approach: Basin Research, v. 14, no. 3, p. 303–318, doi:[10.1046/j.1365-2117.2002.00179.x](https://doi.org/10.1046/j.1365-2117.2002.00179.x).

- Olariu, C., and J. P. Bhattacharya, 2006, Terminal distributary channels and delta front architecture of river-dominated delta systems: *Journal of Sedimentary Research*, v. 76, no. 2, p. 212–233, doi:[10.2110/jsr.2006.026](https://doi.org/10.2110/jsr.2006.026).
- Olariu, C., R. J. Steel, R. W. Dalrymple, and M. K. Gingras, 2012, Tidal dunes versus tidal bars: The sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain: *Sedimentary Geology*, v. 279, p. 134–155, doi:[10.1016/j.sedgeo.2012.07.018](https://doi.org/10.1016/j.sedgeo.2012.07.018).
- Olariu, C., R. J. Steel, M. I. Olariu, and K. Choi, 2015, Facies and architecture of unusual fluvial–tidal channels with inclined heterolithic strata: Campanian Neslen Formation, Utah, USA, in P. J. Ashworth, J. L. Best, and D. R. Parsons, eds., *Fluvial-tidal sedimentology*: New York, Elsevier, *Developments in Sedimentology* 68, p. 353–394, doi:[10.1016/B978-0-444-63529-7.00011-0](https://doi.org/10.1016/B978-0-444-63529-7.00011-0).
- Olariu, M. I., and W. A. Ambrose, 2016, Process regime variability across growth faults in the Paleogene Lower Wilcox Guadalupe Delta, South Texas gulf coast: *Sedimentary Geology*, v. 341, p. 27–49, doi:[10.1016/j.sedgeo.2016.05.013](https://doi.org/10.1016/j.sedgeo.2016.05.013).
- Olariu, M. I., and H. Zeng, 2018, Prograding muddy shelves in the Paleogene Wilcox deltas, south Texas gulf coast: *Marine and Petroleum Geology*, v. 91, p. 71–88, doi:[10.1016/j.marpetgeo.2017.12.027](https://doi.org/10.1016/j.marpetgeo.2017.12.027).
- Pellegrini, C., S. Patruno, W. Helland-Hansen, R. J. Steel, and F. Trincardi, 2020, Clinoforms and clinothems: Fundamental elements of basin infill: *Basin Research*, v. 32, no. 2, p. 187–205, doi:[10.1111/bre.12446](https://doi.org/10.1111/bre.12446).
- Pemberton, S. G., J. A. MacEachern, J. C. V. Wagoner, and G. T. Bertram, 1995, The sequence stratigraphic significance of trace fossils: examples from the Cretaceous foreland basin of Alberta, Canada, in J. C. V. Wagoner, and G. T. Bertram, eds., *Sequence stratigraphy of foreland basin deposits: Outcrop and subsurface examples from the Cretaceous of North America*: AAPG Memoir 64, p. 429–475, doi:[10.1306/M64594C15](https://doi.org/10.1306/M64594C15).
- Peng, Y., R. J. Steel, C. Olariu, and S. Li, 2020, Rapid subsidence and preservation of fluvial signals in an otherwise wave-reworked delta front succession: Early-mid Pliocene Orinoco continental-margin growth, SE Trinidad: *Sedimentary Geology*, v. 395, 105555, doi:[10.1016/j.sedgeo.2019.105555](https://doi.org/10.1016/j.sedgeo.2019.105555).
- Rossi, M., M. Minervini, M. Ghielmi, and S. Rogledi, 2015, Messinian and Pliocene erosional surfaces in the Po Plain-Adriatic Basin: Insights from allostratigraphy and sequence stratigraphy in assessing play concepts related to accommodation and gateway turnarounds in tectonically active margins: *Marine and Petroleum Geology*, v. 66, p. 192–216, doi:[10.1016/j.marpetgeo.2014.12.012](https://doi.org/10.1016/j.marpetgeo.2014.12.012).
- Rossi, V., W. Helland-Hansen, C. Eide, and N. Paterson, 2018, Evidence for muddy deltaic compound clinoforms in the Triassic shelf of northern Pangea: Insights from the Havert Fm. (SW Barents Sea): 20th European Geosciences Union General Assembly, Vienna, Austria, April 4–13, 2018, p. 441.
- Rossi, V. M., W. Kim, J. L. Lopez, D. Edmonds, N. Geleynse, C. Olariu, R. J. Steel, M. Hiatt, and P. Passalacqua, 2016, Impact of tidal currents on delta-channel deepening, stratigraphic architecture, and sediment bypass beyond the shoreline: *Geology*, v. 44, no. 11, p. 927–930, doi:[10.1130/G38334.1](https://doi.org/10.1130/G38334.1).
- Rossi, V. M., and R. J. Steel, 2016, The role of tidal, wave and river currents in the evolution of mixed-energy deltas: Example from the Lajas Formation (Argentina): *Sedimentology*, v. 63, no. 4, p. 824–864, doi:[10.1111/sed.12240](https://doi.org/10.1111/sed.12240).
- Shaffer, B. L., 1990, The nature and significance of condensed sections in Gulf Coast late Neogene sequence stratigraphy: *GCAGS Transactions*, v. 40, p. 767–776.
- Shaw, J. B., D. Mohrig, and S. K. Whitman, 2013, The morphology and evolution of channels on the Wax Lake Delta, Louisiana, USA: *Journal of Geophysical Research: Earth Surface*, v. 118, no. 3, p. 1562–1584, doi:[10.1002/jgrf.20123](https://doi.org/10.1002/jgrf.20123).
- Sømme, T. O., W. Helland-Hansen, and D. Granjeon, 2009, Impact of eustatic amplitude variations on shelf morphology, sediment dispersal, and sequence stratigraphic interpretation: Icehouse versus greenhouse systems: *Geology*, v. 37, no. 7, p. 587–590, doi:[10.1130/G25511A.1](https://doi.org/10.1130/G25511A.1).
- Steel, R. J., C. Olariu, J. Zhang, and S. Chen, 2020, What is the topset of a shelf-margin prism?: *Basin Research*, v. 32, no. 2, p. 263–278, doi:[10.1111/bre.12394](https://doi.org/10.1111/bre.12394).
- Wei, X., R. J. Steel, R. Ravnas, Z. Jiang, C. Olariu, and Z. Li, 2016, Variability of tidal signals in the Brent Delta Front: New observations on the Rannoch Formation, northern North Sea: *Sedimentary Geology*, v. 335, p. 166–179, doi:[10.1016/j.sedgeo.2016.02.012](https://doi.org/10.1016/j.sedgeo.2016.02.012).
- Williams, G. E., 1991, Upper Proterozoic tidal rhythmites, South Australia: sedimentary features, deposition, and implications for the Earth's paleorotation, in D. G. Smith, G. E. Reinson, B. A. Zaitlin, and R. A. Rahmani, eds., *Clastic tidal sedimentology*: Calgary, Canada: Canadian Society of Petroleum Geologists Memoir 16, p. 161–177, doi:[10.13140/RG.2.1.4460.2722](https://doi.org/10.13140/RG.2.1.4460.2722).
- Winker, C. D., 1981, Cenozoic shelf margins, northwestern Gulf of Mexico Basin, in M. B. Edwards, R. R. Berg, J. M. Coleman, W. E. Galloway, J. A. Pacht, E. B. Picou Jr., and H. J. Yorston, eds., *Recognition of shallow-water versus deep-water sedimentary facies in growth-structure affected formations of the Gulf Coast Basin*: Tulsa, Oklahoma, SEPM, v. 2, p. 74–82, doi:[10.5724/gcs.81.02.0074](https://doi.org/10.5724/gcs.81.02.0074).
- Xu, J., J. W. Snedden, W. E. Galloway, K. T. Milliken, and M. D. Blum, 2017, Channel-belt scaling relationship and application to early Miocene source-to-sink systems in the Gulf of Mexico basin: *Geosphere*, v. 13, no. 1, p. 179–200, doi:[10.1130/GES01376.1](https://doi.org/10.1130/GES01376.1).
- Xue, L., 1997, Depositional cycles and evolution of the Paleogene Wilcox strata, Gulf of Mexico Basin, Texas: AAPG Bulletin, v. 81, no. 6, p. 937–953, doi:[10.1306/522B49A1-1727-11D7-8645000102C1865D](https://doi.org/10.1306/522B49A1-1727-11D7-8645000102C1865D).
- Xue, L., and W. E. Galloway, 1995, High-resolution depositional framework of the Paleocene Middle Wilcox strata,

- Texas coastal plain: AAPG Bulletin, v. 79, no. 2, p. 205–230, doi:[10.1306/8D2B14F8-171E-11D7-8645000102C1865D](https://doi.org/10.1306/8D2B14F8-171E-11D7-8645000102C1865D).
- Zhang, J., V. M. Rossi, Y. Peng, R. Steel, and W. Ambrose, 2019, Revisiting Late Paleocene Lower Wilcox deltas, Gulf of Mexico: River-dominated or mixed-process deltas?: *Sedimentary Geology*, v. 389, p. 1–12, doi:[10.1016/j.sedgeo.2019.05.007](https://doi.org/10.1016/j.sedgeo.2019.05.007).
- Zhang, J., R. Steel, and W. Ambrose, 2016, Greenhouse shoreline migration: Wilcox deltas: AAPG Bulletin, v. 100, no. 12, p. 1803–1831, doi:[10.1306/04151615190](https://doi.org/10.1306/04151615190).
- Zhang, J., R. Steel, and W. Ambrose, 2017, Paleocene Wilcox cross-shelf channel-belt history and shelf-margin growth: Key to Gulf of Mexico sediment delivery: *Sedimentary Geology*, v. 362, p. 53–65, doi:[10.1016/j.sedgeo.2017.10.001](https://doi.org/10.1016/j.sedgeo.2017.10.001).