Stacking Patterns, Sediment Volume Partitioning and Facies Differentiation in Shallow-Marine and Coastal-Plain Strata

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Abstract

Fluvial-deltaic strata of the Upper Cretaceous Ferron Sandstone, Western Interior Seaway, form a clastic wedge consisting of eight short-term stratigraphic cycles. The cycles are arranged consecutively in a seaward-stepping, vertically stacked, and landward-stepping stacking pattern. The stacking pattern is a product of fluctuations in accommodation:sediment-supply (A/S) regimes described by intermediate-term base-level cycles.

Each short-term stratigraphic cycle is a progradational/aggradational unit comprising a spectrum of coastal-plain, bay/lagoon/estuary, shoreface and shelf facies tracts. Sediment volumes and sandstone:mudstone ratios were measured separately in coastal-plain and shoreface facies tracts in four of the cycles. Total sediment and total sandstone volumes are partitioned differentially into the two facies tracts in an systematic manner that follows the stacking pattern. The total sediment volume and total sandstone in the shoreface facies tract decreases regularly from seaward- to landward-stepping stacking patterns. The proportion of marine-to-nonmarine sandstone also decreases. This demonstrates increasing sediment storage in uphill continental environments during the transition from seaward- to landward-stepping stacking patterns.

Sediment volume partitioning is accompanied by systematic changes in numerous other stratigraphic and sedimentologic attributes which illustrate the two types of facies differentiation. The first type—stratigraphic control on the types of geomorphic elements which occupy a geomorphic environment—is manifest by the transition from fluvial- to wave-dominated deltas in the progression from seaward- to landward-stepping cycles. The second type—a change in degree of preservation of original geomorphic elements—is illustrated by conspicuous differences in the facies which compose the shoreface and coastal-plain facies tracts. Shorefaces of high-accommodation landward-stepping cycles comprise homogeneous sandstones, whereas shorefaces of low-accommodation seaward-stepping cycles are lithologically heterogeneous containing diverse facies and well-preserved original geomorphic elements. Distributary channelbelt sandstones of landward-stepping cycles are composed of high diversity, well-preserved macroforms and bedforms, whereas those of seaward-stepping cycles are composed of strongly cannibalized, amalgamated, low diversity macroforms and bedforms.

Sediment volume partitioning and facies differentiation are attributed to changing A/S conditions that accompany short- and intermediate-term base level cycles. The A/S conditions control or influence the position and volume of sediment accumulation, the types of geomorphic elements in an environment, and the proportions and completeness of original geomorphic elements which enter the stratigraphic record.

Introduction

This study illustrates the well-organized behavior of the stratigraphic process-response system, and suggests underlying causes for this behavior. We observe systematic variations in numerous stratigraphic and sedimentologic attributes of siliciclastic coastal-plain to shelf strata that are coincident with stacking patterns of stratigraphic cycles. These organized, systematic variations of stratigraphic and sedimentologic attributes are analyzed from the perspectives of conservation laws and stratigraphic base level. Stratigraphic base level describes the balance between the energy required to change accommodation space and the energy used by surficial processes to erode, transport and deposit sediment. Base-level changes are manifest by changes in the ratio of accommodation-to-sediment supply (A/S). Changes in A/S conditions and mass conservation determine the volumes and types of sediment which accumulate in different environments.

Sediment is partitioned differentially into coastal-plain and shoreface facies tracts through time. Changes in the ratios of total sediment volumes within these two facies tracts are accompanied by changes in ratios of nonmarine-to-marine sandstone volumes. Sediment volume partitioning reflects the balance among rates of sediment delivery, rates of reworking and cannibalization of sediment, and rates of net sediment accumulation. Sediment volume partitioning can be explained by variations in the A/S conditions that accompany stratigraphic base-level cycles.

Sediment volume partitioning controls or influences sedimentologic and stratigraphic attributes of all scales including the constituents, associations and successions of facies, the degree of preservation of original geomorphic elements, petrophysical attributes, stratigraphic architecture, and frequency of occurrence of hiatal surfaces of different origins. Two types of facies differentiation are recognized and illustrated. One type is the change in original geomorphic elements which occupy the same environment under variable A/S conditions. The other is the variable degree of preservation of original geomorphic elements and their proportions which enter the stratigraphic record. This produces changes in facies diversity and lithologic heterogeneity in strata which accumulated in the same environment. Heterogeneous shoreface strata of seaward-stepping cycles are responses to lower A/S conditions than the homogeneous sandy shoreface strata of landward-stepping cycles. Similarly, heterogeneous distributary channelbelt deposits of landward-stepping cycles are responses to higher A/S conditions than the homogeneous channelbelt sandstones of seaward-stepping cycles. In homogeneous strata relatively more time is represented by stratigraphic surfaces of discontinuity than by rock, whereas in heterogeneous strata relatively more time is represented by rock than by hiatal surfaces.

Stratigraphic and sedimentologic attributes of all scales and of many types show consistent, systematic patterns of change when viewed from the perspectives of conservation laws and stratigraphic base level. This organization produces transitional facies constituents, associations and successions within a continuum of the preserved products of the same environment. The sedimentologic attributes of facies tracts commonly described in "facies models" are mixtures of the products of geomorphic elements which existed separately during base-level cycles. Future facies models should be constructed from a stratigraphic perspective in which there is a continuum of transitional forms of facies associations and successions which are different products of the same parent.

Stratigraphic Setting and Stacking Patterns

The Upper Cretaceous (Turonian-Coniacian) Ferron Sandstone is a regressive-transgressive wedge which accumulated at the site of a large delta in the foreland basin, east-central Utah (Gardner and Cross, 1994). During that period, sea level was near a maximum highstand, and both accommodation and sediment supply were high. Consequently, time in the Ferron is represented much more by rock than by stratigraphic surfaces of erosion and nondeposition; regional unconformities are absent.

The Ferron consists of eight progradational/aggradational stratigraphic units—short-term stratigraphic cycles—arranged consecutively in seaward-stepping, vertically stacked and landward-stepping geometric patterns (Fig. 1). Each progradational/aggradational unit contains a spectrum of coastal plain, estuary/bay/lagoon, shoreface, and shelf facies tracts. Exceptionally continuous, three-dimensional exposures plus a subsurface data base of geophysical well logs enabled physical correlation of short-term cycles across all facies tracts.

Three temporal and spatial scales of stratigraphic cyclicity are recognized in the Ferron (Fig. 1; Gardner, 1993; Gardner and Cross, 1994). Stratigraphic cycles of each scale record a complete stratigraphic base-level, or energy, cycle *sensu* Wheeler (1964). During an energy cycle, the accommodation/sediment-supply (A/S) ratio decreases unidirectionally to a limit (base-level fall maximum), then increases unidirectionally to another limit (base-level rise maximum). The limits, or "turnaround" points, of these unidirectional trends in A/S increase and decrease are correlated throughout the spatial extent of each stratigraphic cycle. Stratigraphic cycles of each scale are the time-bounded rock units that comprise all strata and diastems produced during a base-level cycle. The initiation points for stratigraphic cycles of all scales must be picked consistently at the same turnaround position. In this study, the initiation point was picked at the base-level rise-to-fall turnaround because it is the most practical; it is the position most easily recognized, frequently documented, consistently picked, and physically traceable.

The stacking pattern of progradational/aggradational stratigraphic units observed and mapped in this study and by Ryer (1977) is the product of changing A/S conditions of the intermediate-term base-level cycle. The seaward-stepping units (1-3; Fig. 1) accumulated during decreasing A/S. The vertically stacked unit (4; Fig. 1) accumulated at the turnaround from intermediate-term base-level fall-to-rise. The landward-stepping units (5-8; Fig. 1) accumulated during intermediate-term base-level rise.

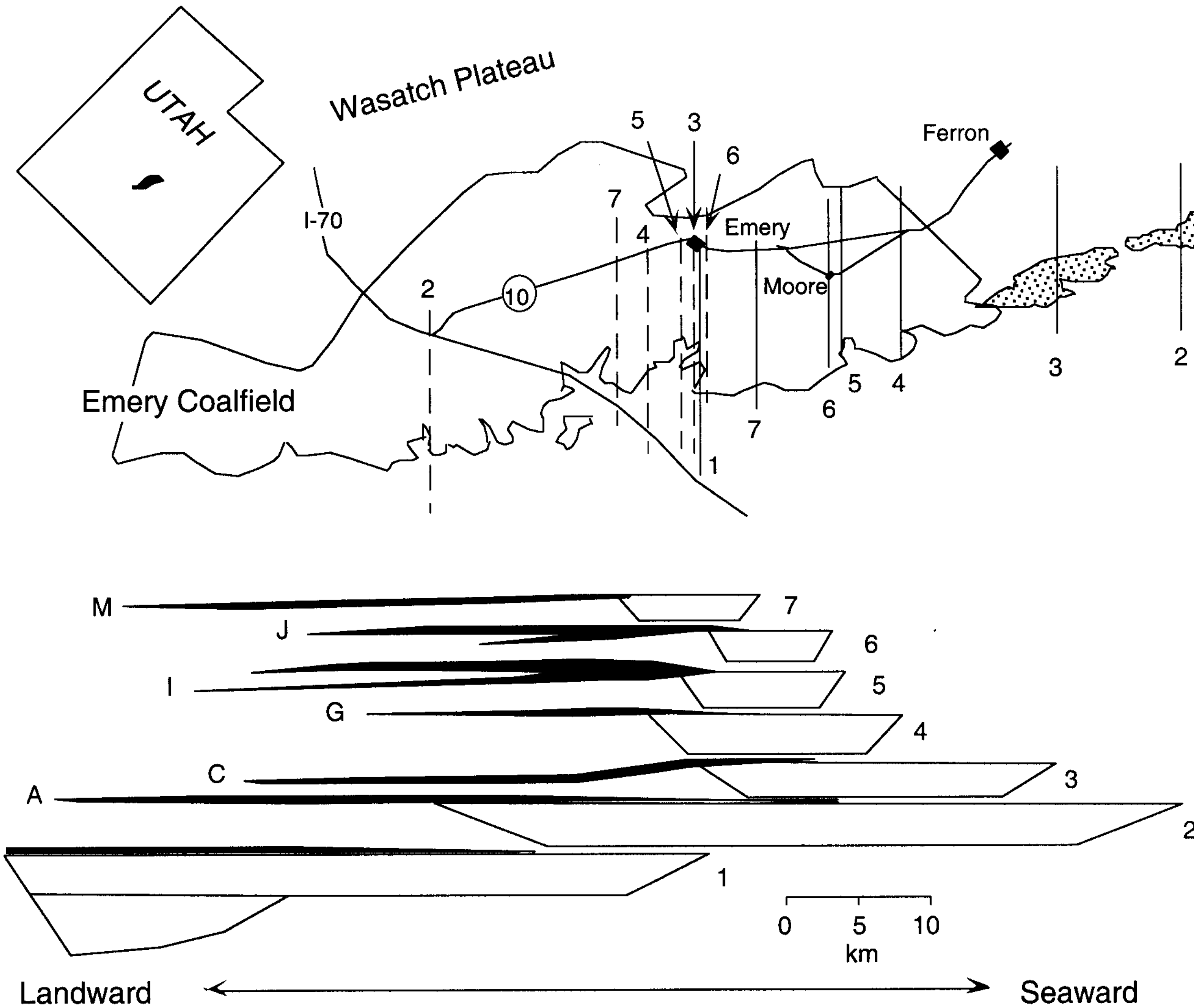

Figure 1—Diagram illustrating the seaward-stepping, vertically stacked and landward-stepping stacking pattern of sort-term stratigraphic cycles in the upper Ferron Sandstone. The stacking pattern records an intermediate-term base-level cycle. Map and cross section show the landward and seaward depositional limits of the shoreface facies tract. The vertical profile from shallow-marine deposits of seaward-stepping cycle 3 illustrates the stratigraphic and sedimentologic responses to short-term (0.3 m.y.) base-level cycles.

Sediment Volume Partitioning

The relative proportions of sediment volumes in coastal-plain and shoreface facies tracts vary with position of the short-term stratigraphic cycle in the stacking pattern. This is one of several important responses to changes in A/S condition at the scale of short- and intermediate-term base-level cycles. As stratigraphic base level rises and intersects (crosses beneath) the earth's surface progressively higher on the topographic profile, the A/S ratio increases and the sediment storage capacity in uphill positions increases. Since more sediment is stored uphill in continental environments, less sediment is available (conservation of mass) for downhill transport and accumulation in shoreface and shelf environments. Conversely, a decrease in the A/S ratio partitions more sediment volume into shoreface and shelf environments and less is stored uphill in continental environments. The degree of sediment volume partitioning in the short-term stratigraphic cycles, as measured by the proportion of sediment volume stored in different facies tracts, changes with changing A/S conditions in the intermediate-term base-level cycle.

Sediment volume partitioning was measured in four of the eight progradational/aggradational units in the upper Ferron. These units were mapped over a 68 mi^2 area using 97 data points from outcrop measured sections, geophysical well logs, and cliff-tape calibrated photomosaics. Sediment volume measurements were normalized to account for paleogeographic variations in position and widths of facies tracts, and incomplete preservation of the

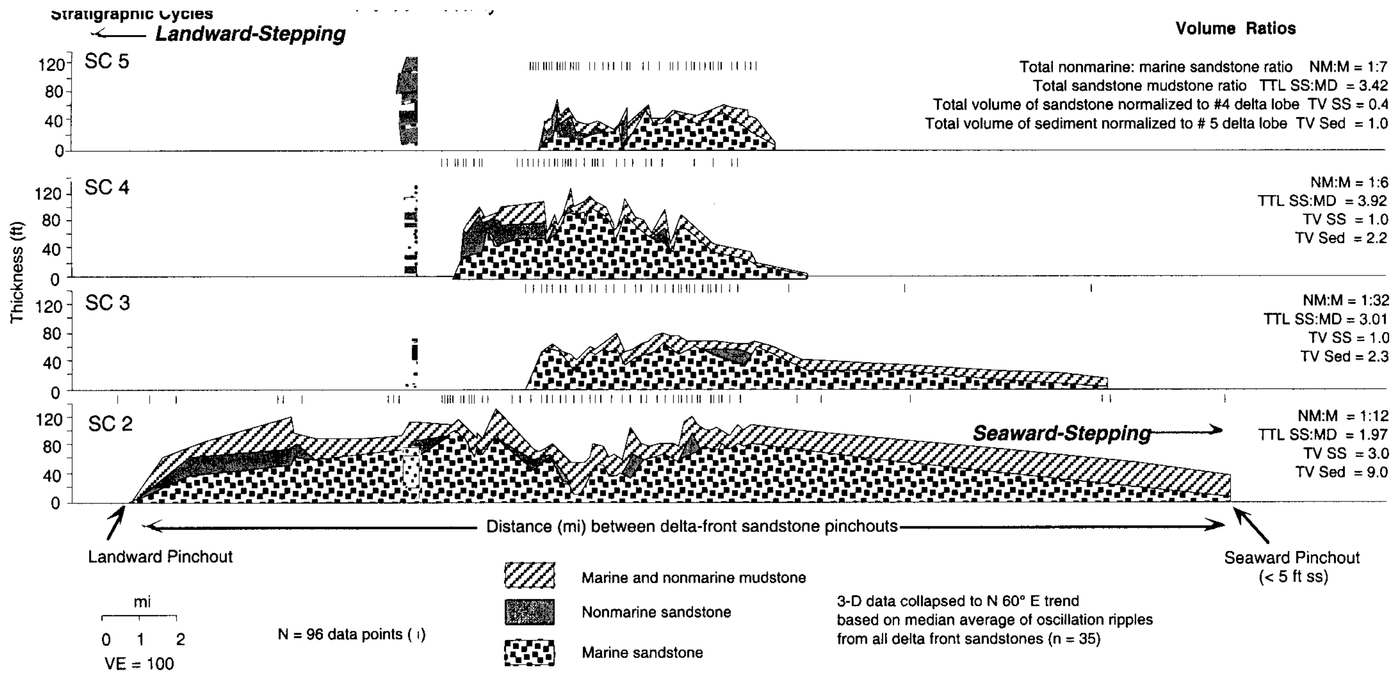

Figure 2—Thickness-distance plot from the upper Ferron Sandstone showing the areal distribution of various lithologies in shallow-marine and coastal-plain strata between the landward and seaward depositional limits of the shoreface facies tract in stratigraphic cycles 2 - 5. The plot orientation is parallel to the direction of progradation. Three-dimensionally distributed data points are collapsed perpendicularly into the depositional dip line, and data points plotted are correlated by linear interpolation. The vertical axis is thickness (m) and the horizontal axis is distance (km), with the origin of the plot set a constant distance from the landward pinch-out of shoreface sandstone.

depositional system from the study area to the thrust front. The most consistent and objective normalization procedure was to measure sediment volumes in continental and marine facies tracts between the landward and seaward depositional limits of the shoreface (delta front) facies tract of each short-term stratigraphic cycle (Fig. 1).

Between these paleogeographic limits, the total sediment volume and the total sandstone and mudstone volumes were measured within shallow-marine and coastal-plain strata separately. This allows comparison of total sediment volumes and lithology ratios of shallow-marine and coastal-plain strata in seaward-stepping, vertically stacked and landward-stepping progradational/aggradational units.

Results are displayed on a thickness-distance plot showing lithology distributions in coastal-plain and shoreface strata between the landward and seaward depositional limits of the shoreface facies tract (Fig. 2). Plot orientation is parallel to depositional dip, as determined from mapped orientations of facies tract boundaries and paleoflow analysis. The plot origin is set a constant distance from the landward depositional limit of the shoreface facies tract. Plots show marine and nonmarine sandstone volumes, total sandstone and mudstone volumes, and total sediment volumes for each progradational/aggradational unit. Sediment volumes are expressed as: 1) sandstone volume ratios of shallow-marine and coastal-plain strata; 2) stratigraphic cycle total sandstone/mudstone volume ratio; and 3) total sediment volume of each stratigraphic cycle. Sediment volume and lithology ratios were calculated for each locality to allow comparison with averaged values on thickness-distance plots.

The total sediment and total sandstone volumes decrease from seaward- to landward-stepping stratigraphic cycles (Fig. 2). The nonmarine:marine sandstone volume ratios of seaward-stepping units 2 and 3 are 1:12 and 1:32, respectively; in vertically stacked unit 4 it is 1:6, and in landward-stepping unit 5 it is 1:7. [Even though data were collected within a strike-oriented swath about 5 miles broad, the sampling of channelbelt sandstones in the coastal-plain facies tract, which are the primary residences of sandstone, is subject to biased position of channelbelts; channelbelts could be in one position in one cycle and in another position in another cycle. Otherwise, measurements of sandstone in the shoreface facies tract and total sediment volume in both facies tracts are not biased. Seaward-stepping cycles record increased sediment volumes in shallow-marine strata, reduced sediment volumes in coastal-plain strata, and a basinward shift in accommodation; shoreface progradation dominates over coastal-plain aggradation. Vertically stacked cycles have little or no offset of facies across cycle boundaries, little shift in the depositional limits of successive stratigraphic cycles, and more even sediment volume distributions in the two facies tracts. Conversely, landward-stepping stratigraphic cycles record increased coastal-plain sediment volumes, reduced shallow-marine sediment volumes, and a landward shift in accommodation; coastal-plain aggradation dominates over shoreface progradation.

Decreases in total sediment and total sandstone volumes reflect decreased shoreface facies tract widths in landward-stepping cycles. Compared with seaward-stepping cycles, progressively increased accommodation and storage capacity in the coastal plain of vertically stacked and landward-stepping cycles reduces the total sediment volume delivered to shallow-marine environments. The shift to increased sandstone storage in the coastal-plain facies tract of vertically stacked and landward-stepping cycles also reflects increased A/S conditions in these cycles.

Because accommodation measures the potential space available for sediment accumulation, the direction of sediment transport does not affect a thickness-distance plot relating sediment volume to accommodation. Sediment delivered from out of the plane (e.g., alongshore transport) of the thickness-distance plot may affect the aspect ratio but not the distribution of sediment volumes in linked facies tracts.

Facies Differentiation in the Shoreface Facies Tract

Accompanying sediment volume partitioning are differences in stratal architecture, facies associations and successions, lithologic diversity, stratification types, connectivity and continuity of lithosomes, and petrophysical attributes of strata which are preserved within identical facies tracts but in different portions of base-level cycles. The term *facies differentiation* (Van Siclen, 1958; Cross, et al., 1993) refers to these changes in sedimentological and stratigraphic attributes during base-level cycles. Facies differentiation reflects both the degree of preservation of original geomorphic elements, and the variations in types of geomorphic elements that existed within a depositional environment at different times. Variation in degree of preservation of geomorphic elements is controlled by the relative balance among rates of sediment addition, removal (cannibalization and winnowing), and net accumulation. Rates of these processes are strongly influenced by sediment volume partitioning which accompanies changing A/S conditions during base-level cycles.

Strata in the shoreface facies tract of seaward- and landward-stepping progradational/aggradational units are very different in terms of lithologic heterogeneity, facies associations and successions, clinoform angles, geometry and aspect ratio, and relative dominance of current-formed versus wave-formed geomorphic elements. Landward-stepping shoreface sandstones deposited in higher A/S regimes are homogeneous, coarser grained, dominated by wave-generated and wave-reworked facies associations, and have narrower facies tract widths. Seaward-stepping shorefaces deposited in lower A/S regimes are heterolithic, characterized by much higher facies diversity of mixed wave and current origins, and contain many fully preserved bedforms and other paleogeomorphic elements. Observations of such differences in stratigraphic and sedimentologic attributes of a facies tract with respect to stacking patterns were made previously, but not explained, by Curtis (1970) for deltas in the Gulf Coast and by MacKenzie (1972) for shorefaces in the Western Interior Seaway.

Lower delta-front facies in landward- and seaward-stepping stratigraphic cycles record the same water-depth transition from storm to fair-weather wavebase, but their stratigraphic and sedimentologic attributes are quite different (Fig. 3). Lower delta-front successions of landward-stepping cycles are thinner (<1- to 4-m thick), and sharp based because they prograde across the flat, shallow water platform formed by the underlying progradational/aggradational unit. They consist of low-diversity erosive-based cosets of amalgamated hummocky cross-stratified sandstone capped by symmetrical ripples, and/or combined-flow asymmetrical ripples. This facies association records dominance of sediment reworking over sediment accumulation and burrowing, with limited preservation of individual bedforms and other paleogeomorphic elements on the seafloor.

By contrast, lower delta-front facies in seaward-stepping cycles consist of a mixture of shallow-water sediment gravity flows, wavy laminated to hummocky cross-stratified sandstone, amalgamated cosets of symmetrical and asymmetrical ripple laminated sandstone, and numerous mudstone drapes, partings and beds. Sandstones and mudstones are approximately equal in proportion, contain more carbonaceous plant debris and soft-sediment deformation, and generally exhibit less burrowing. Bed geometries range from amalgamated to tabular and are broadly lenticular. Preservation of original geomorphic elements is high. These record numerous waning-flow river-flood and waning-flow storm events.

Upper delta-front facies in landward-stepping cycles consist of 1- to 20-m thick, upward-coarsening successions of well-sorted, fine to medium, amalgamated hummocky to swaley (or amalgamated trough cross-stratified) sandstones. The transition from lower to upper delta-front facies is sharp, reflecting a change in sandstone to mudstone ratio from about 5:1 to ≥10:1. Seaward-dipping clinoform surfaces are more steeply inclined but cryptic because of lithologic homogeneity. Trace-fossil diversity is high and includes, in order of abundance, *Skolithos*, *Ophiomorpha*, *Thalassinoides*, *Planolites*, *Diplocraterion*, *Arenicolites*, *Rosselia*, and *Chondrites*.

Upward-coarsening successions of heterolithic mudstones and sandstones of upper delta-front facies in seaward-stepping cycles record increased fluvial influence. Facies and geomorphic elements are diverse and include stacked distributary mouthbars, growth-faults and rotated-slump blocks, and interdistributary bay strata, as well as storm-generated hummocks and swales of the upper shoreface. Long, continuous mudstone drapes and beds separate sandstones deposited by waning-flow river-flood and storm events. Large- and small-scale bedforms are amalgamated to fully preserved. Burrows in sandstone tend to be restricted to the upper portions of beds. Clinoforms are conspicuous and less steep than in shorefaces of landward-stepping units.

Facies differentiation in the shoreface facies tract is explained by sediment volume partitioning in response to base-level cycles. In seaward-stepping stratigraphic cycles, less sediment is stored in the coastal plain, and a proportionally greater volume of sediment is delivered by rivers to paralic, delta-front, shoreface and shelf environments. Consequently, the shoreline is more irregular with lobate and elongate deltaic promontories and embayments. The delta front is fluvial dominated, progrades more rapidly, and rate of sediment accumulation is higher. A broad, low-angle deltaic platform is constructed that increases the frictional drag of incoming waves, thus dissipating wave energy. Higher rates of sediment accumulation and dissipated wave energy provide proportionally less time and efficiency for waves and currents to rework and cannibalize sediment delivered to the shoreface and delta front. The resultant strata comprise a well-preserved, diverse, heterolithic, mudstone-rich assemblage of river-flood and storm events of multiple shallow marine environments.

By contrast, landward-stepping stratigraphic cycles are characterized by more total sediment storage and increased proportion of mud to sand in the coastal plain. Consequently, a reduced sediment volume which is initially sandier is delivered to the delta front. Progradation and sediment accumulation rates are reduced in the sandier delta front, and waves and currents have proportionally more time to cannibalize and winnow shoreface sediment. Resulting delta-front facies are homogeneous, sand-rich, and record significant sediment redistribution and reworking by waves which reduces facies diversity.

The progressive changes from fluvial- to wave-dominated delta-front facies in seaward- to landward-stepping short-term cycles reflect the sensitivity of delta-front profiles to the balance between ocean waves and currents and sediment discharge from distributary channels. Changes in offshore platform slope and delta-front profile reflect variations in sediment flux. Wright and Coleman (1973) showed that high-flux, river-dominated deltas contain low-gradient slopes, and low-flux, wave-dominated deltas contain steeper slopes. Changes in delta morphology are accompanied by changes in smaller scale geomorphic element preserved in the delta. These changes produce different facies mosaics and facies proportions within similar water-depth facies associations of different short-term stratigraphic cycles.

The shoreface facies tracts of Ferron progradational/aggradational units show good examples of the two types of facies differentiation. The first type—stratigraphic control on the types of geomorphic elements which occupy a geomorphic environment—is manifest by the conspicuous transition from fluvial- to wave-dominated deltas in the transition from seaward- to landward-stepping stratigraphic cycles. The only control on the change in delta morphology we can detect is the change in A/S conditions that accompany the stacking pattern of small-scale stratigraphic cycles. Different delta types do not appear to have resulted from changes in climate, drainage-basin size, discharge, fetch, shelf width, water depth, tectonic regime or other control. Instead, the flux of sediment to the delta front varied as a function of differential sediment storage in the coastal-plain facies tract during changing A/S regimes. As the sediment flux and composition changed, so did the relative balance between fluvial input and marine reworking and cannibalization, and different delta morphologies resulted. The other type of facies differentiation—a change in degree of preservation of original geomorphic elements—is exemplified by conspicuous sedimentologic differences in the facies which compose the shoreface facies tracts of seaward- and landward-stepping stratigraphic cycles. Increased facies diversity and degree of preservation is typical of landward-stepping cycles, whereas amalgamation, cannibalization, and low facies diversity is typical of seaward-stepping cycles. Again, this change is attributed to changing A/S conditions that control the proportions and completeness of original geomorphic elements which are preserved.

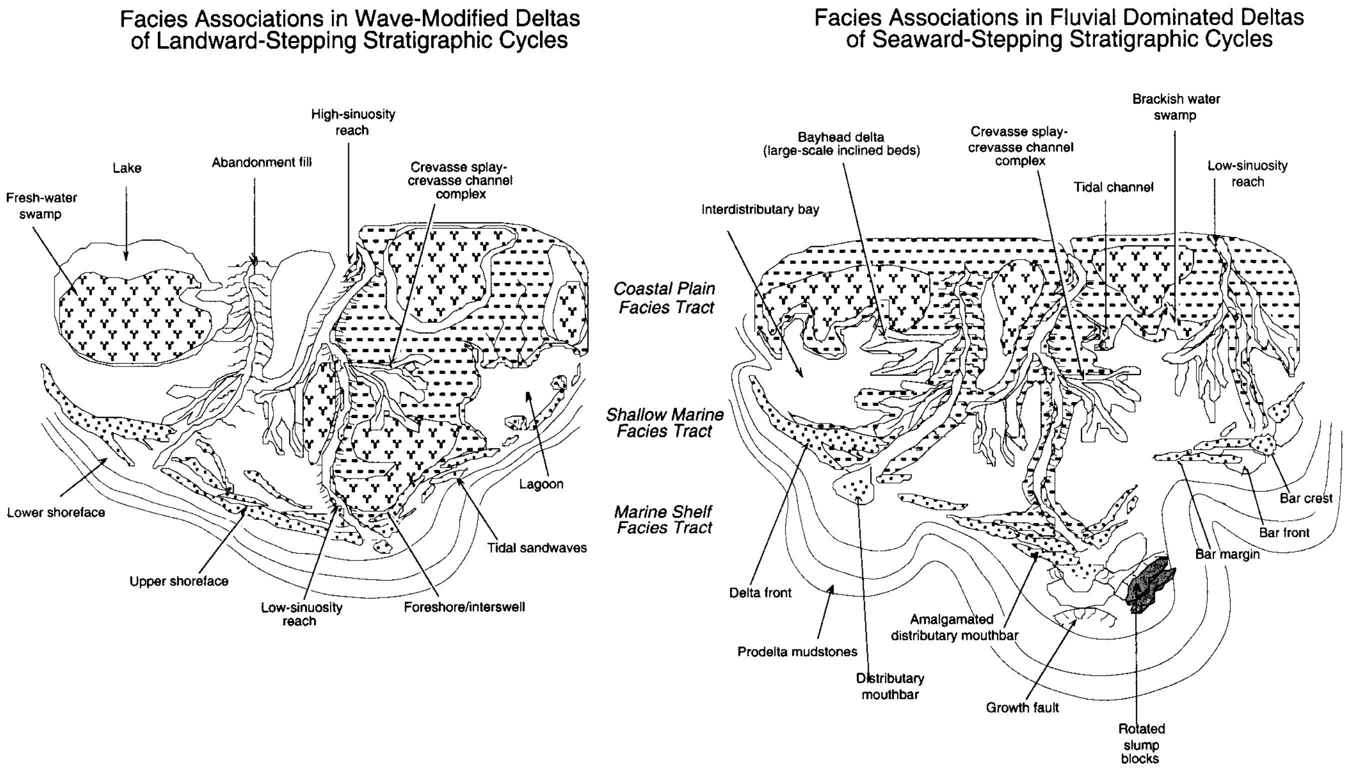

Figure 3—Schematic diagram showing marine-shelf, shallow-marine, and coastal-plain facies tracts and facies associations of (A) seaward-stepping and (B) landward-stepping stratigraphic cycles in the upper Ferron Sandstone. Changes in delta morphology and facies components are related to sediment volume partitioning in shallow-marine and coastal-plain deposits. In seaward-stepping cycles, fluvial-dominated deltas show pronounced elongate to lobate morphologies. Deltas of landward-stepping stratigraphic cycles are wave-dominated with slightly lobate and straight morphologies.

Facies Differentiation in the Coastal-Plain Facies Tract

Stratigraphic cycles in the coastal-plain facies tract contain alternating organic-poor, sand-rich facies (distributary-channel and crevasse-splay/crevasse-channel sandstones) recording base-level fall, and organic-rich, sandstone-poor facies (paludal and floodplain mudstones, carbonaceous shales and coal) recording base-level rise. Coastal-plain strata contain the same facies in all short-term stratigraphic cycles, regardless of position in the stacking pattern. However, the proportions of facies, geometry and size of architectural elements, and degree of preservation of geomorphic elements change regularly with the stacking pattern. The coastal-plain facies tract of landward-stepping cycles contains greater sandstone and total sediment volumes but lower sandstone to mudstone ratios than the coastal-plain facies tract of seaward-stepping cycles. This tendency is progressive through the stacking pattern.

Coastal-plain strata of seaward-stepping cycles thin upward, and have progressively increasing sandstone-to-shale ratios, decreasing facies diversity, deeper channel incisions, laterally extensive erosion surfaces, and thin aggradational paleosols and coal seams. Coastal-plain strata of vertically stacked cycles contain laterally expanded multistory and multilateral distributary-channelbelt sandstones which interfinger with heterolithic crevasse splay and crevasse channel deposits. Vertically stacked cycles also contain higher proportions of mudstone and carbonaceous mudstone, poorly developed coals, the coarsest sediment fraction, and approximately equal channelbelt-to-floodplain volume ratios. Coastal plain strata of landward-stepping units contain a high channelbelt-to-floodplain ratio, channelbelt sandstones interfinger with a high proportion of crevasse-channel/crevasse-splay complexes and amalgamated coal beds up to 10 m thick. Thin, laterally extensive coals commonly cap landward-stepping short-term cycles.

Distributary channels of approximately the same scale, morphology and bank-full dimension fed the shorefaces in all cycles. Yet many sedimentologic attributes of distributary channelbelt sandstones are radically different in cycles at different positions in the stacking pattern. In distributary channelbelt sandstones, the composition and thickness of lag deposits, the types and geometries of channel sandstone bodies, the degree of preservation of original bedforms, and the diversity of facies record the changes in A/S regime and concomitant sediment volume partitioning (Fig. 2).

Distributary channelbelt sandstones have a grossly similar cross-sectional geometry and a similar internal progression of facies changes in all cycles. They all have a characteristic "funnel" or "longhorn steer" cross-sectional shape. At the base, steep-sided channelbelt margins are narrow (the nose of the steer); the channelbelt margins expand 4 to 10 times in width toward the top and have low-gradient margins (the "horns" of the steer). The progression of facies attributes is from highly interconnected, amalgamated, cannibalized, laterally restricted, vertically stacked sandstone bodies at the base, to expanded, more open framework and more fully preserved, laterally stacked sandstone bodies toward the top. Even though channelbelt sandstones in all cycles share this basic motif, several other sedimentologic changes record the changes in A/S and the sediment volume partitioning that accompany the short- and intermediate-term base-level cycles.

Distributary channelbelt sandstones of high-accommodation, landward-stepping cycles are typically 15-25 m thick and 1-1.5 km wide. They contain a diverse assemblage of moderately interconnected, cut-and-fill, low-sinuosity, high-sinuosity and abandonment-fill macroforms 5-20 m thick (Fig. 3). Macroforms often are separated by mud drapes or lags. Mud-matrix-supported, mud-boulder-intraclast lag deposits on channel and macroform scour bases are up to 1 m thick and laterally continuous (hundreds of meters). Internal accretion and reactivation surfaces of equal length record lateral and downstream barform migration. Bedforms, cut-and-fill macroforms, and accretionary macroforms are well preserved (low amalgamation and little cannibalization). Facies diversity within macroforms is high, including thick and thin sets of trough cross-stratification, planar-tabular stratification, horizontal lamination, convolute lamination and other structures indicative of fluidization, fully preserved straight-crested dunes climbing the backs of larger barforms, and thick sets of ripple and climbing ripple lamination.

By contrast, channelbelt sandstones of low-accommodation, seaward-stepping cycles are of comparable thickness but only a few hundred meters wide. They contain a low diversity of highly interconnected (amalgamated) cut-and-fill and low-sinuosity, erosive-based macroforms 5-10 m thick (Fig. 3). Bedforms and macroforms are strongly cannibalized and amalgamated, resulting in very low facies diversity (typically >95% by volume of thin sets of trough cross-stratified sandstone). Channel and macroform scour bases are occasionally and discontinuously overlain by sand-matrix-supported, mud-pebble-intraclast lags 2-20 cm thick.

The coastal-plain facies tracts of Ferron progradational/aggradational units show good examples of facies differentiation produced by differences in degree of preservation of geomorphic elements under varying A/S regimes. In high accommodation landward-stepping stratigraphic cycles, coastal-plain facies are diverse, reflecting preservation of multiple geomorphic elements. Many of the original bedforms and barforms of distributary channels are fully or nearly fully preserved. By contrast, the diversity of coastal-plain facies in low accommodation seaward-stepping stratigraphic cycles is very low, reflecting preservation of only those geomorphic elements which are most easily preserved. The original bedforms and barforms of distributary channels are intensely cannibalized and amalgamated.

Facies Models in a Stratigraphic Context

Facies models summarize the facies associations presumed indicative and characteristic of particular sedimentary environments. They are constructed through synthesis, reduction and simplification of observations from multiple specific examples to abstract the "essence," or the essential facies elements of a particular environment, from the "noise," or variations from whatever is perceived as the norm (Walker, 1984). The only requirement for selection of examples is that the example must be a product of a particular geomorphic environment. Facies models are constructed with the presumption that the preserved stratigraphic record of an environment is similar to, and a composite of, all geomorphic elements in that environment. Accordingly, the geomorphic elements in an environment are preserved in the same ratios as facies in strata. This presumption requires that the mosaic of geomorphic elements which form the patchwork quilt on the earth's surface at an instant in time aggrade in place to form a stratigraphic facies mosaic of identical complexity and areal distribution. If facies associations and successions representing a single depositional environment are collected from different stratigraphic cycles, or different parts of the same base-level cycle, the resulting facies model of that depositional environment is derived from a mixture of unrelated elements which never co-existed.

Facies models are specific to each environment; they do not mix or merge the facies of laterally linked environments. A facies model for laterally linked braidplain-lake-alluvial fan environments does not exist, but each environment has its own models. Environments identified as geomorphically distinct have separate facies models attached to them. Multiple facies models exist for different river morphologies (e.g., braided, meandering, anastomosed) and for different delta morphologies (wave-, fluvial- and tide-dominated).

Facies models are static. Facies attributes, associations and successions are collapsed from multiple examples into a single geomorphic and sedimentologic character set presumed to exist at an instant in time. Facies models are constructed with the presumption that the stratigraphic products (preserved depositional remnants) of a particular depositional environment are similar from place to place and from time to time. Models do not recognize that given identical geomorphic elements in a particular environment, changes in degree of preservation (volume and proportion) of those elements will create major differences in the facies observed in the stratigraphic record.

None of these characteristics of facies models employs four-dimensional stratigraphic appreciation for the accumulation of sediment. Facies models ignore the fact that sediments accumulate during the migration of laterally linked environments. The mosaic of geomorphic environments does not aggrade in place producing a stratigraphic product resembling the geomorphic parent.

This study demonstrates that stratigraphic processes influence the types of geomorphic elements which compose an environment, as well as the proportion and degree of preservation of elements which enter the stratigraphic record. Changing A/S conditions during base-level cycles control sediment volume partioning which, in turn, contributes to the two types of facies differentiation. Future, more accurate facies models should be constructed from a stratigraphic perspective in which there is a continuum of transitional forms of facies associations and successions which are different products of the same parent.

Conclusions

At the scale of the Ferron clastic wedge, sediment accumulated in different paleogeographic positions through time to form a series of stratigraphic cycles arranged in a seaward-stepping, vertically stacked and landward-stepping stacking pattern. Geographic partitioning of sediment volumes at this scale is related to the changes in accommodation:sediment-supply (A/S) conditions during an intermediate-term base-level cycle.

Within each stratigraphic cycle, sediment was partitioned into depositional environments in different volumes and ratios during short-term base-level cycles. Superposition of the two scales of base-level cycles causes systematic changes in sediment volume partitioning through time. The total sediment volume and total sandstone in the shoreface facies tract decreases regularly from seaward- to landward-stepping stacking patterns. The proportion of marine-to-nonmarine sandstone also decreases. This demonstrates increasing sediment storage in uphill continental environments during the transition from seaward- to landward-stepping stacking patterns.

One product of the changing A/S regime and sediment volume partitioning is a change in delta morphology. Deltas in seaward-stepping cycles are fluvial dominated, whereas those in landward-stepping cycles are wave-dominated. The change in delta morphology is related to the change in sediment storage capacity uphill in continental environments. This is an illustration of one type of facies differentiation, where stratigraphic processes control the types of geomorphic elements which occupy a particular depositional environment.

Sediment volume partitioning at the scale of short-term stratigraphic cycles also effects the rate of net sediment accumulation in different environments, and reflects the balance between rates of sediment addition and rates of sediment reworking and cannibalization. Changes in A/S conditions during a short-term cycle control or modulate the degree of cannibalization and amalgamation of geomorphologic elements that compose an environment. Variations in facies diversity, facies associations and successions, lithologic heterogeneity and petrophysical properties within a facies tract are manifestations of changing A/S conditions. Shorefaces of high-accommodation landward-stepping cycles comprise homogeneous sandstones, whereas shorefaces of low-accommodation seaward-stepping cycles are lithologically heterogeneous containing diverse facies and well-preserved original geomorphic elements. Distributary channelbelt sandstones of landward-stepping cycles are composed of high diversity, well-preserved macroforms and bedforms, whereas those of seaward-stepping cycles are composed of strongly cannibalized, amalgamated, low diversity macroforms and bedforms. These examples illustrate the other type of facies differentiation, where stratigraphic processes control the proportions and ratios of original geomorphic elements which are preserved.

Sediment volume partitioning and facies differentiation during gradually changing A/S regimes create radically different facies constituents, associations and successions from the same geomorphic environment. The stratigraphic products are transitional forms along a continuum from high to low A/S conditions for each facies tracts. Existing facies models assume the products of orphic environments are similar regardless of time, place and condition of accumulation. Facies models are insensitive to stratigraphic controls on facies associations and successions. Moreover, most are incorrectly constructed from observations of facies elements that never coexisted. If facies models are to be useful for stratigraphic prediction, they must be calibrated to A/S conditions that drive volumetric partitioning and facies differentiation. A new generation of stratigrahpically sensitive facies models is required.

Systematic changes in numerous stratigraphic and sedimentologic attributes emphasize the well-ordered behavior of the stratigraphic process-response system, and demonstrate systematic linkages among attributes of all scales and many types. These attributes are complementary records of multiple, interdependent processes which may be analyzed from the simple perspectives of conservation laws and stratigraphic base level. The systematic organization of disparate and diverse data types is the basis for robust stratigraphic prediction. From a knowledge of attributes at one scale, attributes at another scale may be predicted.

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