HIGH RESOLUTION SEQUENCE STRATIGRAPHY—THE EAST COULEE DELTA, ALBERTA[1]

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ABSTRACT: The fundamental concept on which sequence stratigraphy is based is that stratal architectures develop in response to the interaction between base-level change and sediment flux. A small lacustrine fan-delta at East Coulee, Alberta, illustrates these principles and demonstrates that sequence stratigraphic concepts are scale- and time-independent. This fan-delta formed in a matter of days in a roadside drainage ditch as water level rose and then fell. Changes in the subaqueous space available for sediment to fill (i.e., accommodation) resulted in the development of a succession of systems tracts analogous to those formed within sedimentary basins over much longer time frames.

Deposition began during lake-level rise with progradation of a fan-deltaic wedge. Accelerating lake-level rise resulted in a backstepping of the shoreline and deposition of a transgressive systems tract. Subsequent lake-level fall resulted in subaerial exposure of the relatively steep delta front and caused incised valley formation and deposition of a lowstand delta. This stratigraphic response to base-level fall is typical of lowstand systems tract development on basin margins characterized by high-relief slopes (e.g., passive margins). Further lake-level fall resulted in minor additional valley incision and development of a second lowstand delta on a surface characterized by lower relief as lowering water level exposed a flatter physiography. This development of lowstand deltas and coastlines during base-level fall constitutes a *forced regression* of Posamentier et al. (1990) and is typical of lowstand systems tracts on basin margins characterized by gentle slopes.

In spite of its small size, this example clearly illustrates that sequence stratigraphic principles apply to lacustrine as well as marine settings and at all spatial and temporal scales.

INTRODUCTION

Sequence stratigraphic concepts were first introduced by Vail et al. (1977) through a discussion of seismic stratigraphy. Building on the work of Sloss (1963), they, too, recognized the occurrence of unconformity-bounded sequences. However, the sequences described by Vail et al. (1977) are an order of magnitude smaller and can be bounded by correlative conformities as well as unconformities. Vail et al. (1977) observed, using seismic data, that there was a marked similarity of coastal onlap patterns in a number of sedimentary basins distributed throughout the world. They concluded that a globally effective driving mechanism such as eustatic change was the most likely cause of this synchroneity. The mechanics of this relationship were left unclear until Jervey (1988) suggested by mathematical modelling a causal relationship between eustatic change and coastal onlap pattern. Posamentier and Vail (1988) and Posamentier et al. (1988) refined this approach, recognizing and describing the component systems tracts within the depositional sequence and relating them to fluctuations of *relative* sea level. [Relative sea-level change defines the change of subaqueous space made available for sediment to fill by combining the effects of sea-surface movement (i.e., eustasy) and sea-floor movement (i.e., total subsidence) (Posamentier et al. 1988).]

Variations of relative sea level influence both the landward and seaward limits of terrigenous sediment distribution. In the landward direction, the absolute limit of terrigenous sedimentation defines the coastal onlap curve and can comprise either non-marine sediment, paralic coastal plain sediment, or near-shore marine shoreface sediment. In the seaward direction, an absolute limit of terrigenous sedimentation can be difficult to define; the section thins and is eventually expressed as a condensed section (Loutit et al. 1988). Nonetheless, the distribution of this condensed section facies is influenced by relative sea-level change, so that during times of rapidly rising relative sea level the shoreline transgresses and the condensed section facies spreads and encroaches further landward.

Typically, because of data base constraint as well as

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commonly incomplete sections in the landward parts of basins due to erosion there, the landward limit of terrigenous sediment distribution is not observed. In contrast, on the seaward side, the seaward-most occurrence or limit of terrigenous sediment can be said to occur where there is a facies change to the condensed section. Condensed sections and associated flooding surfaces commonly are recognized more readily (e.g., Galloway 1989) than unconformities associated with basinward shifts of coastal onlap recognized toward the landward limit of terrigenous sediment distribution. Nonetheless, though the recognition of these flooding surfaces may appear more straightforward at first, unconformities can also be recognized, though with greater difficulty. The choice of unconformities as sequence boundaries (in contrast with maximum flooding surfaces) is made because they represent stratigraphically significant sedimentation breaks within sedimentary successions. The sediments between unconformities, which constitute a depositional sequence, represent a continuum of sedimentation, albeit at varying rates and by varying processes. The recognition of unconformities is also significant because these surfaces are typically associated with the juxtaposition of hydrocarbon reservoir lithofacies with source and seal lithofacies (see discussion in Posamentier and James 1992).

The East Coulee fan delta (Fig. 1) formed along the margin of a large puddle within a roadside drainage ditch during a period of high runoff following a rainstorm. The delta measured c. 2.3 m across and c. 1.8 m along dip. The ditch within which it formed was c. 2.8 m wide and c. 30 m long. Its depth at the center was c. 50 cm at its maximum and c. 10 cm at its minimum. Varying "puddle" level (i.e., base level) resulted in a succession of systems tracts including a highstand/shelf margin, transgressive, and two lowstand systems tracts. In addition, other features such as ravinement surfaces, longshore drift-associated beach deposits, wave cut bevels and incised valleys were recognized. In this example, the effect of varying sediment flux and stream discharge may have played a role in the physical stratigraphic development, but the effects of base-level change are emphasized here. The objective of this paper is to show how stratal patterns evolve in response to variations in base level using a naturally-occurring analogue. This example confirms that *sequence stratigraphic principles are scale- and time-independent.*

An important attribute of the East Coulee example is that it illustrates and is analogous to the stratal development along basin margins characterized by relatively steep slopes (e.g., passive margins) as well as those characterized by relatively gentle slopes (e.g., ramp margins such as those associated with submerged continental shelves or intracratonic basins). As is generally true, basin margin physiography varies with stands of sea level. In the case of the East Coulee Delta, when "puddle" level was high, the near-shore basin floor was characterized by steep slopes and when "puddle" level was low, the near-shore basin floor was characterized by gentle slopes. As will be shown, these differences in slope yielded different stratal architectural responses.

SEQUENCE STRATIGRAPHY OF BASIN MARGINS

The physical stratigraphy of any basin margin is a function of the interactions of eustasy, subsidence (including that of tectonic origin as well as compaction), and sediment flux (e.g., Posamentier et al. 1988). However, the physiography of the basin margin also plays a key role in the stratigraphic development. The physical stratigraphy, the nature of the stratal unit bounding surfaces, and the occurrence of such features as incised valleys and submarine fans will depend largely on the local physiography, which, in turn, can be a function of local structuring as well as pre-existing depositional relief. A passive margin will likely be characterized by the development of incised valleys, submarine canyons, and submarine fans in response to relative sea-level fall (e.g., the Hudson Channel, Apron, and Canyon on the east-coast United States continental shelf: Ewing et al. 1963; Knott and Hoskins 1968; Uchupi 1970). These features occur when the continental shelf and the upper continental slope are subaerially exposed. In contrast, a basin margin characterized by a gentle or "ramp" margin (e.g., the western Canadian Sedimentary Basin) will likely not develop incised valleys, submarine canyons or submarine fans.

The stratal geometry of the East Coulee Delta, as for any margin, can be explained by analysis of changes in the rate of new space added, or accommodation. This has been discussed by Posamentier and Vail (1988), who show, in their figures 1 through 5, sequence and systems tract development on a basin margin characterized by a steep continental slope. Their figure 27 illustrates possible sequence and systems tract development on basin margins characterized by a gentle ramp profile. This figure shows a pattern of lowstand deposition (i.e., "shelf-perched lowstand deposits") characterized by seaward jumps of the shoreline associated with relative sea-level fall. Similar stratal geometries associated with base-level fall were suggested by Plint (1988) for the Cretaceous Cardium Formation in the western Canada sedimentary basin.

EAST COULEE DELTA—DESCRIPTION

The East Coulee fan delta comprises at least three progradational lobes that have built into a small roadside drainage ditch (Fig. 1). The lobes are arcuate in plan view and are built by streams characterized by a braided pattern. The grain size distribution within each of these lobes is silt to very fine sand. The delta lobes are progressively younger in a basinward direction. A stream cut gulley (Incised Valley "y" on Fig. 1) cuts across the largest and landwardmost lobe (Unit A on Fig. 1), originating at the fan-delta apex and continuing across to the basinward most delta lobe. The depth of incision is greatest across Unit A and diminishes downdip. This stream-cut gulley served as the conduit for sediment that fed two smaller delta lobes (Units C and D on Fig. 1). Two strike-parallel escarpments (Escarpments 1 and 2 on Fig. 1) are observed atop the largest lobe. Several minor gulleys (or valleys) are observed to terminate at this escarpment (e.g., Incised Valley "x" on Fig. 1).

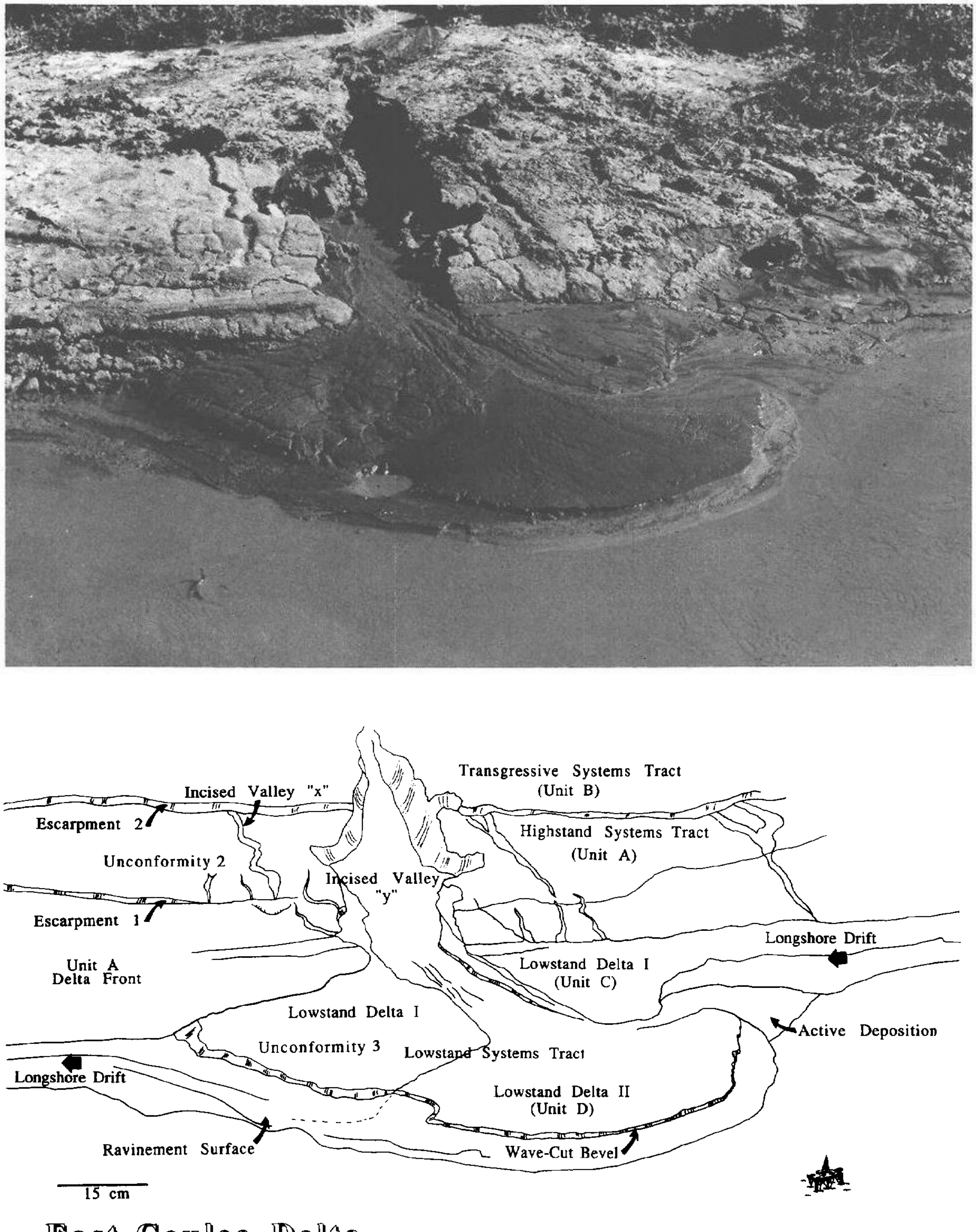

FIG. 1.—Fan-delta at East Coulee, Alberta; the delta measured c. 2.3 m across and 1.8 m along dip and prograded into a roadside drainage ditch c. 2.8 m wide and c. 30 m long during a short interval following a rain storm. Highstand, transgressive, and two lowstand systems tracts are recognized.

EAST COULEE DELTA—STRATIGRAPHY

Highstand/Shelf Margin and Transgressive Systems Tracts

Deposition of the East Coulee delta (Fig. 1) was initiated during and immediately after a period of heavy rain in April, 1989, near the central Alberta, Canada, community of East Coulee. Because it was not possible to examine the internal stratal patterns of this unit, the physical stratigraphy described here is based on observations of external morphology. (Trenching was attempted, but high fluid content of the substrate resulted in significant slope instability. Consequently, nearly immediate slumping precluded examination of the physical stratigraphy.) The presently visible deposits of the earliest delta (Unit "A" on Fig. 1) were inferred to have been associated with higher stands of lake level. It is reasonable to assume that delta sedimentation was initiated shortly after the onset of rainfall (i.e., at an initially lower lake level). During the ensuing rising lake level, the delta could have prograded or retrograded, depending on the ratio between sediment flux and the rate of accommodation increase associated with lake-level rise. In either case, aggradation would have occurred, resulting in a landward migration of coastal onlap as shown in Figure 2A.

The occurrence of an erosional escarpment (escarpment 1 on Fig. 1) is interpreted as a wave-cut bevel associated with transgression of the shoreline (Fig. 2B). A subsequent acceleration of lake-level rise resulted in an overstepping of the bevel and a rapid landward migration of the shoreline to a position landward of escarpment 2. It is possible that the bevel formation was followed by minor lake-level fall. Evidence for this interpretation is the occurrence of a small incised gulley or valley (Incised Valley "x" on Fig. 1) atop Unit A feeding a small delta just seaward of Escarpment 1 (Fig. 2C). Ancient stranded lowstand (?) shorelines/deltas that may be analogous to these deposits have been described from the Cretaceous Cardium Formation, Alberta, Canada (Plint et al. 1987; Plint 1988) and the Cretaceous Viking Formation, Alberta, Canada (Posamentier and Chamberlain 1989; Posamentier et al. 1990).

Following these events, an interpreted major flooding resulted in shoreline migration back towards the apex of Unit A (Fig. 2D). Subsequently, a decrease in the rate of lake-level rise or a stillstand led to resumed shoreline regression and progradation of Unit B (Figs. 1 and 2E). The evidence for Unit B being a distinct and younger progradational unit is the occurrence of incised valley "x" disappearing beneath Unit B at Escarpment 2 (Fig. 1) and the distinctly different surface texture observed at the tops of the units. The smoother surface texture atop Unit A could be the result of smoothing processes accompanying the flooding event. This would imply that Unit B was never transgressed.

The internal stratigraphy of Unit A could not be examined because of the unconsolidated nature of the sediment. However, Figure 3 illustrates the three most likely stratal patterns. In each case, a highstand systems tract would be identified, with a possible associated shelf-margin systems tract shown in Figure 3C (see discussion of shelf margin systems tract in Posamentier and Vail 1988). The highstand/shelf margin systems tract (Unit A in Fig. 1) would be bounded at the base by a basal unconformity and at the top by the marine flooding surface exposed distal to Escarpment 2. This depositional unit is overlain by a single backstepping or retrograding unit comprising the transgressive systems tract (i.e., Unit B).

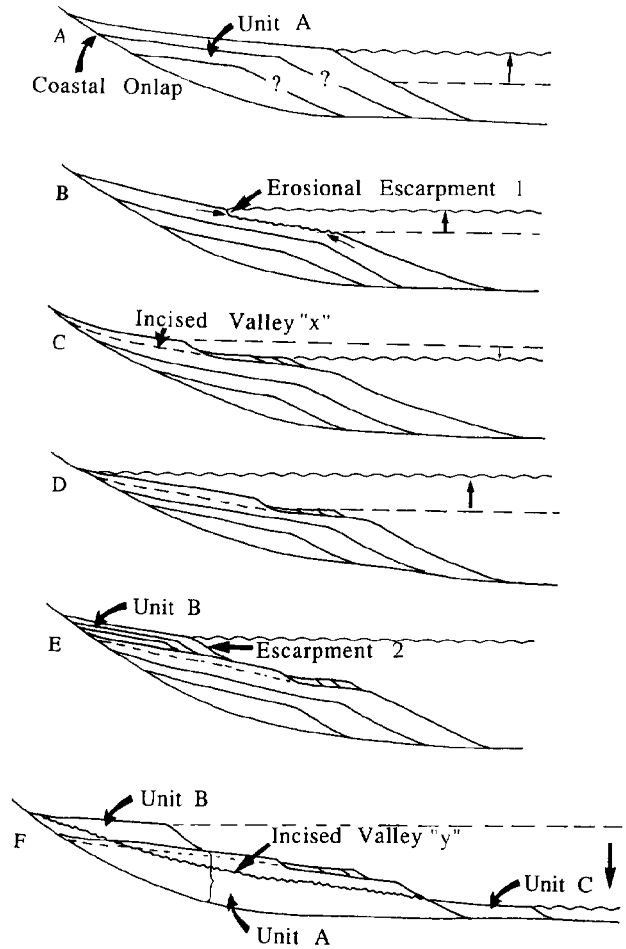

FIG. 2.—Schematic evolution of East Coulee Delta stratal geometry (see discussion in text).

Lowstand Systems Tracts

During lake-level (i.e., base level) fall, the delta plain of Unit B ceased to be an active depocenter and became a zone of bypass. A stillstand during the interval of lake-level fall could have produced Escarpment 2 (discussed above). As lake level continued to fall, the steeper slopes of the delta front were exposed. The longitudinal profile of the principal stream was extended by the additional freshly exposed, albeit steeper, stream segment. The stream responded to the new steeper segments by downcutting to re-establish its graded or equilibrium profile, thus excavating Incised Valley "y".

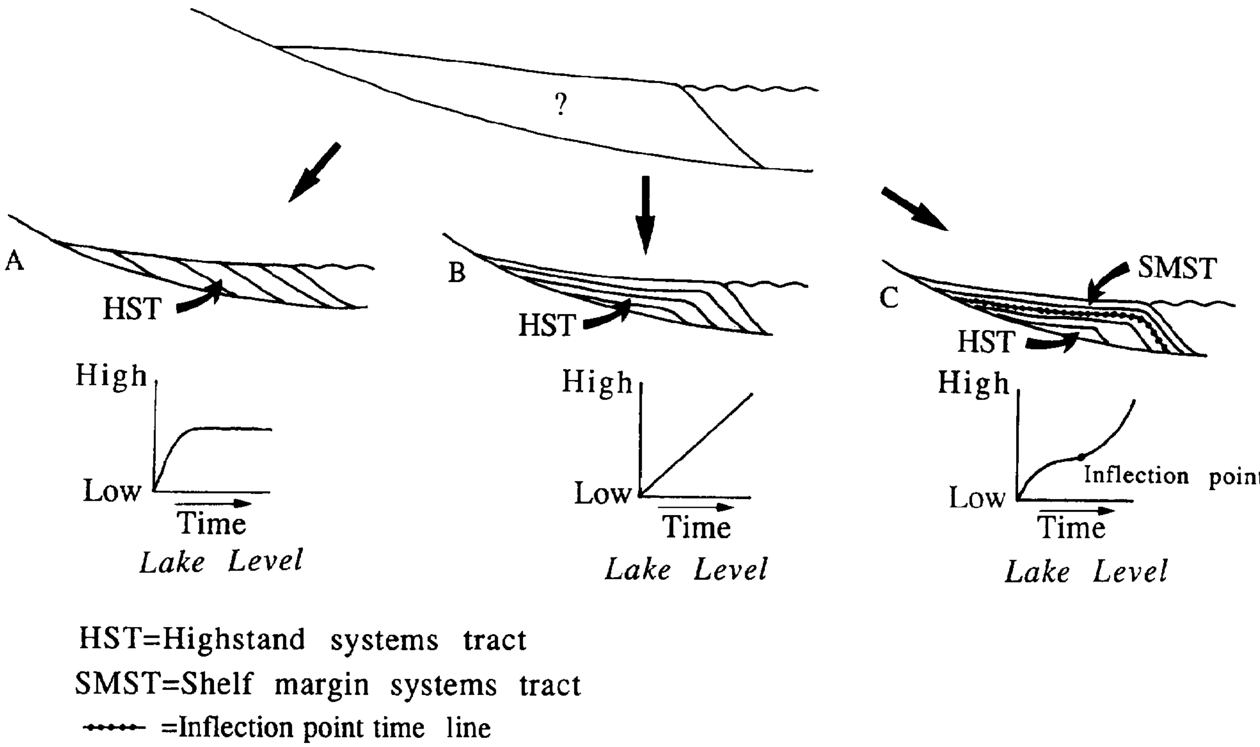

FIG. 3.—Possible physical stratigraphy within Unit A. A) Physical stratigraphy occurring in response to initial rapid rate of lake level rise and then flattening out to zero rate of lake level rise. B) Physical stratigraphy occurring in response to constant rate of lake level rise. C) Physical stratigraphy occurring in response to a decelerating and then accelerating rate of lake level rise. Note, sediment flux is assumed to be constant.

Figure 4 illustrates the fluvial response to base-level fall when lowered base level exposes slopes that are steeper than or equal to the fluvial graded profile. The small-scale incised valleys associated with Escarpment 2 develop for the same reasons. Valley incision occurring in response to base-level fall is common on basin margins characterized by relatively steep continental slopes. In this type of setting (e.g., Gulf of Mexico, east-coast United States), relative sea-level fall may expose relatively steep slopes, enhancing the likelihood of significant fluvial incision.

The subaerially-exposed upper surface of the highstand/shelf margin systems tract becomes the unconformity surface and therefore a sequence boundary (Fig. 1). In a larger-scale setting, soil development is likely to occur on these interfluves at this time. The preservation of these soils would depend upon the depth of scour associated with the ravinement surface formed during the next transgression.

The incised valleys fed lowstand deposits (i.e., the lowstand systems tract) that developed seaward of the highstand/shelf margin delta plain (Unit A) and onlapped the delta front (Fig. 1). This seaward translation of the shoreline strictly due to base-level fall constitutes a *forced regression* (Posamentier et al. 1990). This type of regression is in marked contrast to seaward translations of the shoreline resulting from an excess of sediment supply relative to shelf space available (i.e., accommodation). This latter type of regression results from continual progradation and

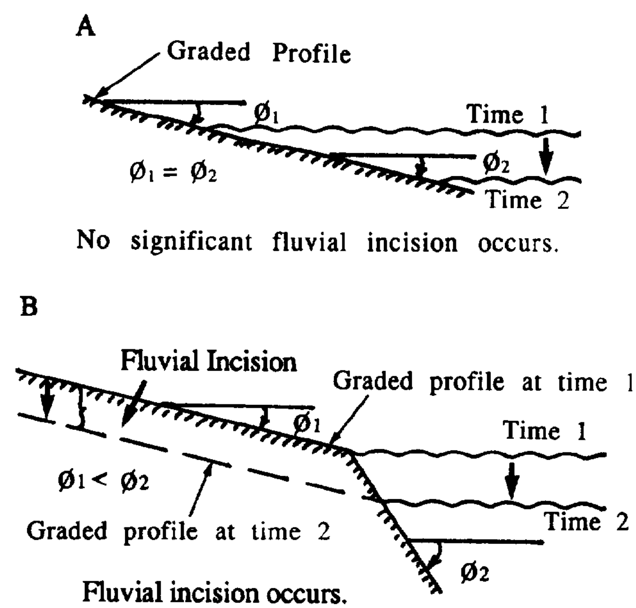

FIG. 4.—The occurrence of fluvial incision in response to the angle of slope exposed due to base-level fall. A) Base level fall from time 1 to time 2 exposes a slope at approximately the same angle as that of the graded profile; no significant fluvial incision occurs. B) Base level fall from time 1 to time 2 exposes a slope steeper than that of the graded profile; significant fluvial incision occurs.

could be termed a "normal" regression. The *forced regression* is characterized by discrete seaward jumps of the shoreline (Posamentier et al. 1990). The lowstand delta comprising Unit C (LSD I) is an example of this type of regression (Fig. 1). Note that the location of onlap as well as the shoreline of Unit C occurred significantly basinward of the immediately preceding shoreline of Unit B located at or near escarpment 2 (Fig. 2F).

Lake level probably stabilized at this time, allowing Unit C to prograde. Lake depth was at this time significantly less than during preceding highstand/shelf margin and transgressive systems tracts times (Units A and B). The slope of the Unit C delta front (LSD I) may have been lower, since the delta was prograding into shallower water. If this were the case, a renewed lake-level fall would result in another forced regression, less incision than previously, and the deposition of Unit D (LSD II: Fig. 1). With this base-level fall, the LSD I delta plain and the upper part of its delta front were exposed and became zones of sedimentary bypass. If the slope of the exposed LSD I delta front and prodelta were relatively low, then it could have been comparable to and not significantly out of grade with the equilibrium profile associated with channels flowing across the LSD II delta plain. Consequently, only relatively minor fluvial incision into the delta plain of LSD I occurs (Fig. 1) as the new stream segment added (i.e., the exposed part of the LSD I delta front) is only slightly out of grade (Fig. 4).

It is suggested, therefore, that with this change of physiography at the shelf margin as the basin drains the system henceforth is analogous to a basin characterized by a gentle ramp margin, such as might be observed within an intracratonic basin or some foreland basins (e.g., the western Canadian sedimentary basin and some of the Cretaceous western interior basins of the U.S.). Basin margins with broad submerged shelves (e.g., the U.S. Gulf Coast or the U.S. Atlantic coast) also would respond similarly (until the entire shelf were to be subaerially exposed).

Lake-level stillstand (and/or significant reduction of sediment flux and stream discharge) following LSD II deposition resulted in initiation of shoreline transgression and the development of a wave-cut bevel and beginning of development of a ravinement surface (Fig. 1). Longshore drift from right to left (Fig. 1) redistributes lowstand sediments of Units C and D and smears them along the exposed delta front of the preceding highstand/shelf margin systems tract (Unit B) (compare with fig. 24 in Posamentier and Vail 1988).

A subsequent lake-level rise and transgression of the shoreline, although it has not yet occurred here, may result in erosion of some of the delta plain sediments of the two lowstand as well as the highstand/shelf margin systems tracts. This shearing action producing a ravinement surface may eliminate any traces of the incised valleys across LSD I which supplied LSD II. Consequently, the preserved deposits would consist of "beheaded" LSDs I and II with no apparent feeder valley systems. A similar lack of preserved feeder valleys for lowstand deposits is observed in the Viking Formation, Alberta, Canada (Posamentier and Chamberlain 1989) and the Cardium Formation, Alberta, Canada (Bergman and Walker 1988). This transgressive erosion also explains the apparent absence of evidence for subaerial exposure at the top of what should have been subaerially exposed highstand deposits landward of the lowstand shorelines.

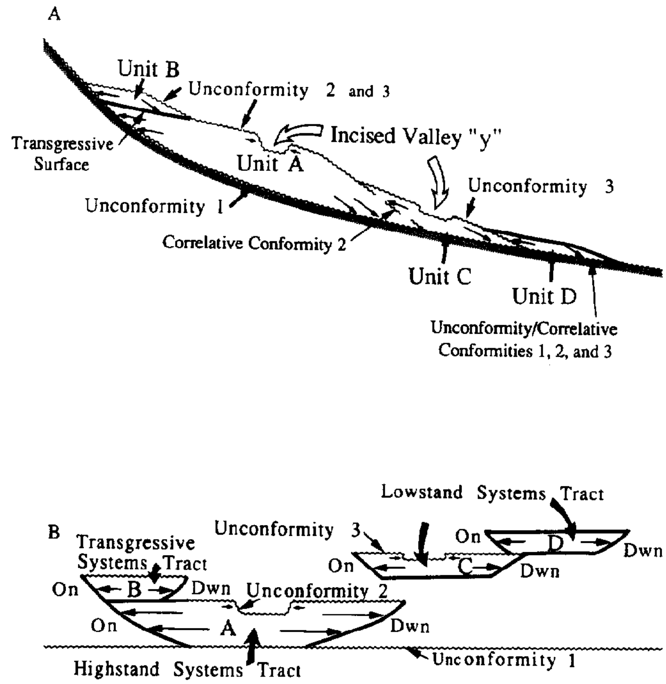

FIG. 5.—Schematic dip-oriented cross section across the East Coulee delta (A). Four depositional units (A, B, C, and D) are recognized and correspond to the highstand/shelf margin, transgressive, and two lowstand systems tracts respectively. The chronostratigraphic chart (**B**) (i.e., Wheeler Diagram) illustrates the distribution in time *and* space of each depositional unit. Note the seaward jump of coastal onlap between units B and C as well as between units C and D.

Unconformities

The East Coulee delta is characterized by a number of unconformities or sequence boundaries as illustrated in Figure 5. The initial unconformity (1) (Fig. 5) is a Type I unconformity that lies at the base of the highstand/shelf margin systems tract and was onlapped by this unit as lake level rose. The succeeding unconformities are associated with lake-level falls and are therefore classified also as Type I unconformities in the sense of Vail and Todd (1981) and Posamentier and Vail (1988). With the onset of lake-level fall, an unconformity (2) (Fig. 5) develops atop Units A and B and is inferred to underlie Units C and D as a correlative conformity. The unconformity is associated with the prominent incised valley system on the transgressive and upper part of the highstand/shelf margin systems tracts (Units A and B). Another unconformity (3) develops atop Unit C in response to renewed lake-level fall. This unconformity amalgamates with unconformity 2 landward of Unit C and distally underlies Unit D as a correlative conformity.

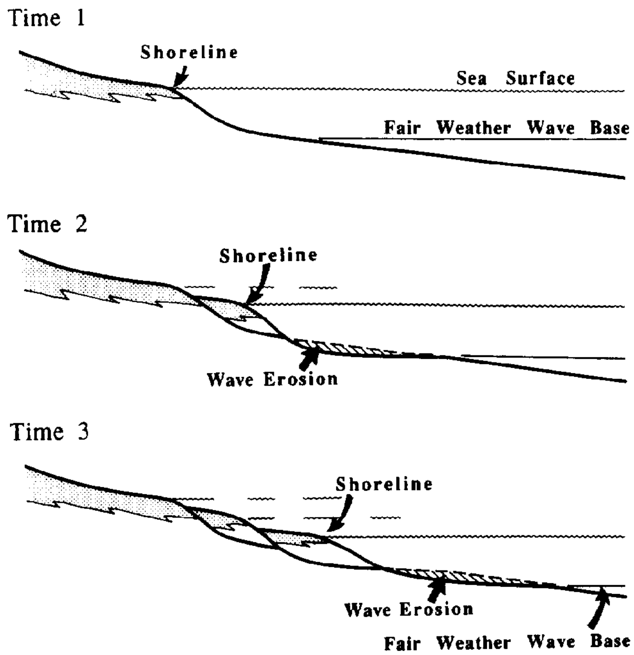

FIG. 6.—Evolution of sharp-based shoreface deposits in response to relative sea-level fall. Lowering relative sea level from time 1 to time 3 results in successive lowering of fair-weather wave base and scour of the sea floor in advance of the prograding shoreface (after Plint 1988).

If a subsequent lake-level rise were to occur and result in transgression, the transgressive ravinement surface and the unconformity would be merged on the interfluves to form an E/T surface (Erosion and Transgression of Plint et al. 1987). Within the incised valleys, the unconformities or sequence boundaries may not be coincident with the transgressive surface. If lowstand deposits (e.g., fluvial sediments) occur there, then the unconformity would occur at their base and the transgressive surface would separate the lowstand deposits from overlying transgressive (e.g., estuarine) deposits. If lowstand deposits are not present, then the unconformity and sequence boundary would be coincident. An example of this in the subsurface occurs within the Viking Formation at Crystal Field, Alberta. At this location, an incised valley is observed to be cutting into regional offshore deposits and is filled with sediments ranging from fluvial to estuarine to open marine in origin (Reinson et al. 1988). Where fluvial deposits overlain by estuarine deposits occur at the base of the incised valley, an unconformity and sequence boundary is interpreted at the base of the fluvial deposits and a transgressive surface at the contact between the fluvial and estuarine deposits. Where fluvial deposits are absent and estuarine sediments occur at the base of the incised valley, the unconformity and sequence boundary are coincident with the transgressive surface (Allen and Posamentier 1991). A similar interpretation is made for sediments filling the Gironde estuary, southwest France (Allen and Posamentier 1991).

The nature of unconformity 3 where it underlies Unit D is a matter of speculation. Posamentier and Vail (their fig. 27, 1988) have suggested that with a forced regression the relatively abrupt introduction of coarser sediment associated with this abrupt basinward shift of depocenter may result in a sharp based coarsening upward succession. Plint (1988) has further observed that a lowered base level would result in a lowering of fair-weather wave base and consequent erosion of the sea floor (Fig. 6). This erosion (a *regressive surface of erosion,* Clifton, personal communication, 1988) would tend to enhance the sharp contact between the underlying highstand/shelf margin systems tract and the overlying lowstand systems tract. Such contacts have been observed for a number of different formations including the Dunvegan Formation (Plint, personal communication, 1988) and the Cardium Formation (Plint 1988) in Alberta, Canada as well as other formations (Posamentier et al. 1990).

CONCLUSIONS

The East Coulee delta complex has evolved in response to varying lake level. A succession of depositional units (i.e., systems tracts) and discontinuity surfaces was observed. The physical stratigraphy here is analogous to that which characterizes larger-scale basin margins influenced by fluctuating relative sea level, suggesting that sequence stratigraphic concepts are scale- and time-independent, and this delta affords a useful three-dimensional view of an evolving basin margin. Attributes of both a shelf/slope and ramp physiography can be observed in this small-scale analogue.

Unconformities or sequence boundaries develop in response to relative sea-level or base-level fall. They can be characterized by significant valley incision (e.g., unconformity 1) on basins with a shelf/slope physiography and by minor or no preserved valley incision on basins with ramp margins (as would occur atop Unit C following subsequent shoreline transgression). Both cases are variations of Type I unconformities and both are accompanied by *forced regressions.*

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