THE STRATIGRAPHIC ORGANIZATION OF INCISED-VALLEY SYSTEMS ASSOCIATED WITH RELATIVE SEA-LEVEL CHANGE

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ABSTRACT: The most common form of incised-valley system develops during a lowering in base level associated with a fall in relative sea level. This form of incised-valley system provides the most complete, and at times, the only evidence of lowstand to early-transgressive deposition in shelf and/or shallow ramp depositional settings. Incised-valley systems of this type are characterized by a fluvially-eroded, elongate paleotopographic low, generally larger than a single channel, which displays an abrupt basinward shift of facies at its base. The valley fill typically begins to accumulate during base-level rise, and may contain deposits of the following highstand and subsequent sea-level cycles.

Two major varieties of incised valley occur during a lowering of sea level: (i) incised-valley systems that have their headwaters in a (mountainous) hinterland and cross a "fall line" (or knickpoint) are here considered to be *piedmont incised-valley systems*, and (ii) incised-valley systems that are localized within low-gradient coastal plains and that do not cross a "fall line" are here termed *coastal-plain incised-valley systems*. An incised-valley system that is filled during one depositional sequence is termed a *simple fill*, whereas a *compound fill* records multiple cycles of incision and deposition.

The fill of an incised-valley system that forms in response to a lowering of base level is divisible into three segments: (i) the seaward reaches of the incised valley (SEGMENT 1) is characterized by backstepping (lowstand to transgressive) fluvial and estuarine deposits, overlain by transgressive marine sands and shelf muds; (ii) the middle reach of the incised valley (SEGMENT 2) consists of the drowned-valley estuarine complex that is developed at the time of maximum transgression, overlying a lowstand to transgressive succession of fluvial and estuarine deposits like those in segment 1; and (iii) the innermost reach of the incised valley (SEGMENT 3) lies headward of the transgressive estuarine limit, and extends to the point where changes in relative sea level no longer control fluvial style. Segment 3 is characterized by fluvial deposits throughout its depositional history; however, the fluvial style may change systematically due to changes in base level and the rate of creation of accommodation space.

The stratigraphic organization of these incised-valley systems is characterized by a number of stratigraphically-significant surfaces that differ greatly in their origin, geographic extent, and chronostratigraphic significance. Filling of the valley may begin during the lowstand, but typically continues through the succeeding transgression. Thus, the *transgressive surface* (i.e., the flooding surface separating the Lowstand Systems Tract and the Transgressive Systems Tract) should be present in the lower portion of the fill. It may occur within fluvial deposits or at the fluvial-estuarine contact in segments 1 and 2, and at a correlative change in fluvial depositional style in segment 3. Erosion by tidal currents in tidal inlets or other tidal channels creates a *tidal ravinement surface* which is confined to the incised valley in segment 1 and the seaward part of segment 2. More regional erosion by waves at the retreating shoreface produces a *wave ravinement surface* that separates fluvial and/or estuarine sediments from overlying marine deposits in segment 1. Both of these surfaces are diachronous, and could become amalgamated with the sequence boundary. In the idealized case, a *maximum flooding surface* may extend throughout the incised-valley fill, passing from its typical position within marine shales in segment 1, through the center of the estuarine deposits in segment 2, into fluvial sediments in segment 3. However, rapid relative sea-level fall after the end of the transgression, or renewed sea-level rise after valley filling (but before the onset of significant progradation), may prevent development of the maximum flooding surface. Compound valley fills may contain multiple sets of these surfaces.

INTRODUCTION

An *incised-valley system* consists of both an incised valley and its depositional fill, and may provide the most complete (and at times, only) evidence of lowstand to transgressive deposition in shelf-slope and/or shallow-ramp, marine depositional settings (Suter and others, 1987; Van Wagoner and others, 1990; Allen and Posamentier, this volume; Belknap and others, this volume; Thomas and Anderson, this volume; Fig. 1). Incised valleys have been recognized for many years (e.g., Fisk, 1944), and are known throughout the geologic record, from the Precambrian (e.g., Dyson and von der Borch, this volume; Levy and others, this volume) through to the Quaternary and modern units (e.g., Allen and Posamentier, this volume; Ashley and Sheridan, this volume; Belknap and others, this volume; Kindinger and others, this volume; Roy, this volume; Thomas and Anderson, this volume). See Dalrymple and others (this volume) for a more complete historical summary.

Interest in incised-valley systems is based upon their increasing significance in three related contexts.

1) Recent application of sequence-stratigraphic principles to the stratigraphic record, and the recognition of the association between incised valleys and regionally mappable unconformity (i.e., sequence-bounding) surfaces. When recognized, these surfaces are a major key to the development of a chronostratigraphic framework that provides a better understanding of reservoir distribution in shallow-marine and non-marine depositional environments (e.g., Vail and others, 1977; Weimer, 1983, 1984; Posamentier and Vail, 1988; Posamentier and others, 1988; Van Wagoner and others, 1988, 1990; Galloway, 1989). Thus, the recognition of incised valleys is an important tool in the correct subdivision of the stratigraphic record.
2) The recognition that economically-significant quantities of hydrocarbons are produced from reservoirs hosted by the fill of incised-valley systems (e.g., Harms, 1966; Berg, 1976; Van Wagoner and others, 1990; Zaitlin and Shultz, 1990; Dolson and others, 1991; Brown, 1993). Indeed, Brown (1993) has estimated that approximately

Incised-valley Systems: Origin and Sedimentary Sequences, SEPM Special Publication No. 51

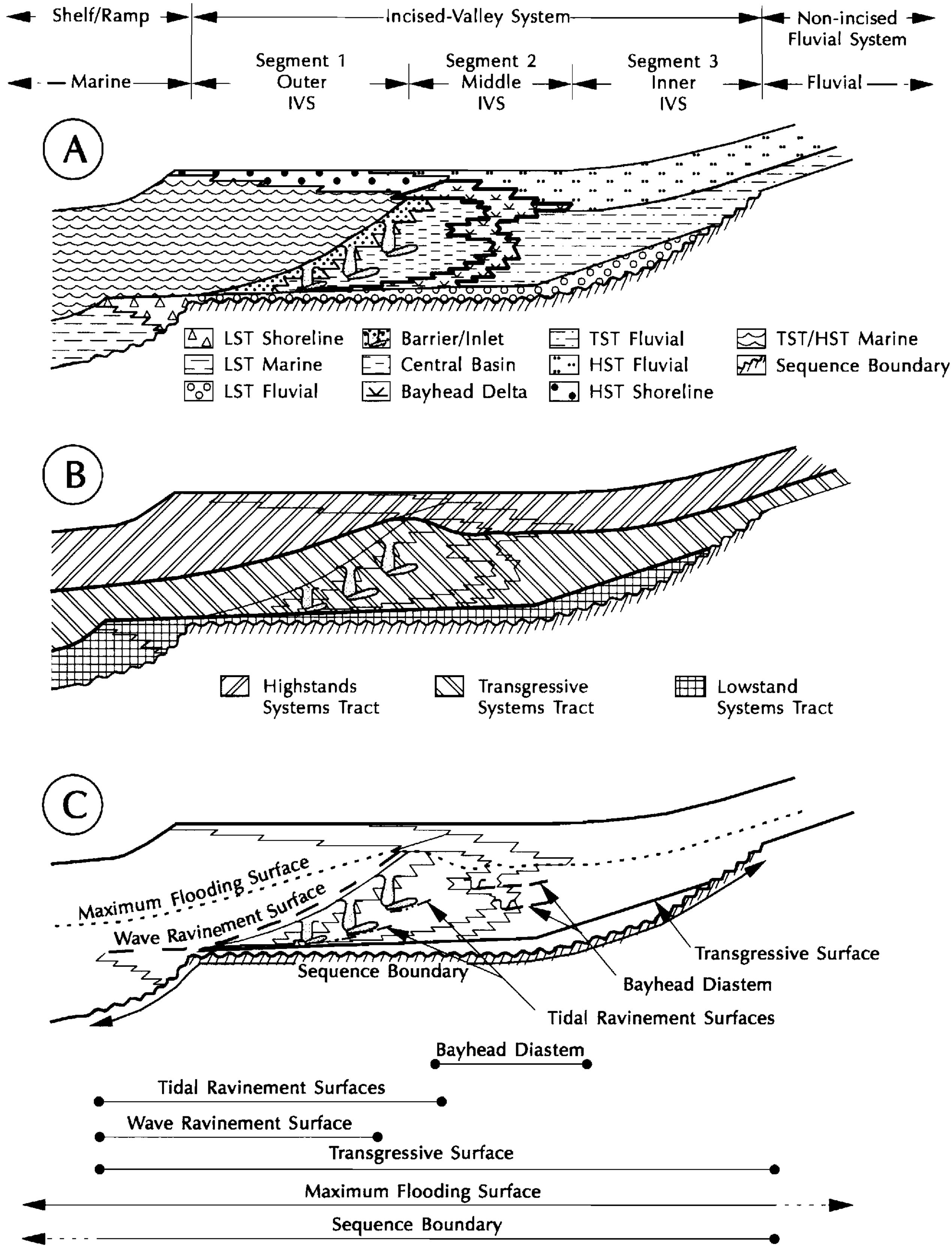


FIG. 1.—Idealized longitudinal section of a simple incised-valley system showing the distribution of: (A) depositional environments; (B) system tracts; and (C) key stratigraphic surfaces. See text for discussion of the segments and surfaces. Note that segments 1 and 3 are typically much longer than segment 2, and are compressed here for ease of presentation. LST = lowstand systems tract; TST = transgressive systems tract; HST = highstand systems tract.

25% of all off-structure clastic reservoirs containing conventional hydrocarbons, world-wide, are produced from lowstand to transgressive, incised-valley deposits. Thus, the internal facies architecture of incised-valley fills is of critical importance to both the exploration for, and exploitation of, hydrocarbon reserves.

3) Finally, there is heightened concern about global warming and the associated rise of sea level that will flood low-lying and heavily-populated, coastal-valley areas (Komar and Enfield, 1987; Davis and Clifton, 1987; Demarest and Kraft, 1987). An increased understanding of the evolutionary changes that occur within incised-valley systems, based on the integrated study of modern, Quaternary and ancient analogs, may allow better prediction of the environmental effects and permit a better response to future sea-level change.

Objectives

The factors discussed above indicate that incised-valley systems are of greater importance than their volumetric contribution to the stratigraphic record would suggest. Despite this, there have been no attempts to develop a "generalized" facies model (cf. Walker, 1992) for the entire incised-valley system; models that do exist concentrate on specific segments of, or depositional styles within, incised-valley systems (e.g., Roy, 1984, this volume; Allen, 1991; Allen and Posamentier, 1993, this volume; Dalrymple and others, 1992; Reinson, 1992; Schumm and Ethridge, this volume; Thomas and Anderson, this volume). The aim of this paper is to present an idealized facies model for an incised-valley system that is produced by fluvial incision associated with a drop in relative sea level (Figs. 1, 2). The model will be presented in a sequence-stratigraphic context, generally following the methodology of Van Wagoner and others (1988, 1990). The model will incorporate a synthesis of the papers published in this volume, and original work stemming from research in modern and ancient incised-valley systems. We recognize that our knowledge of incised-valley systems is incomplete, and acknowledge that our model will require refinement as additional data become available.

Two separate (but inter-connected) issues arise when one is attempting to develop a generalized model for incised-valley systems. The first issue is the establishment of criteria by which an incised-valley system may be recognized in the stratigraphic record. The second issue is the description of the (predictable) stratigraphic organization of the incised-valley fill. This paper will start by defining the nature of an incised-valley system, and will then summarize the recognition criteria that stem from this definition, and address the nature and stratigraphic organization of the incised-valley fill. The paper will conclude by commenting on aspects of the variability and preservation potential of deposits within incised-valley systems.

BASIC ATTRIBUTES OF INCISED-VALLEY SYSTEMS

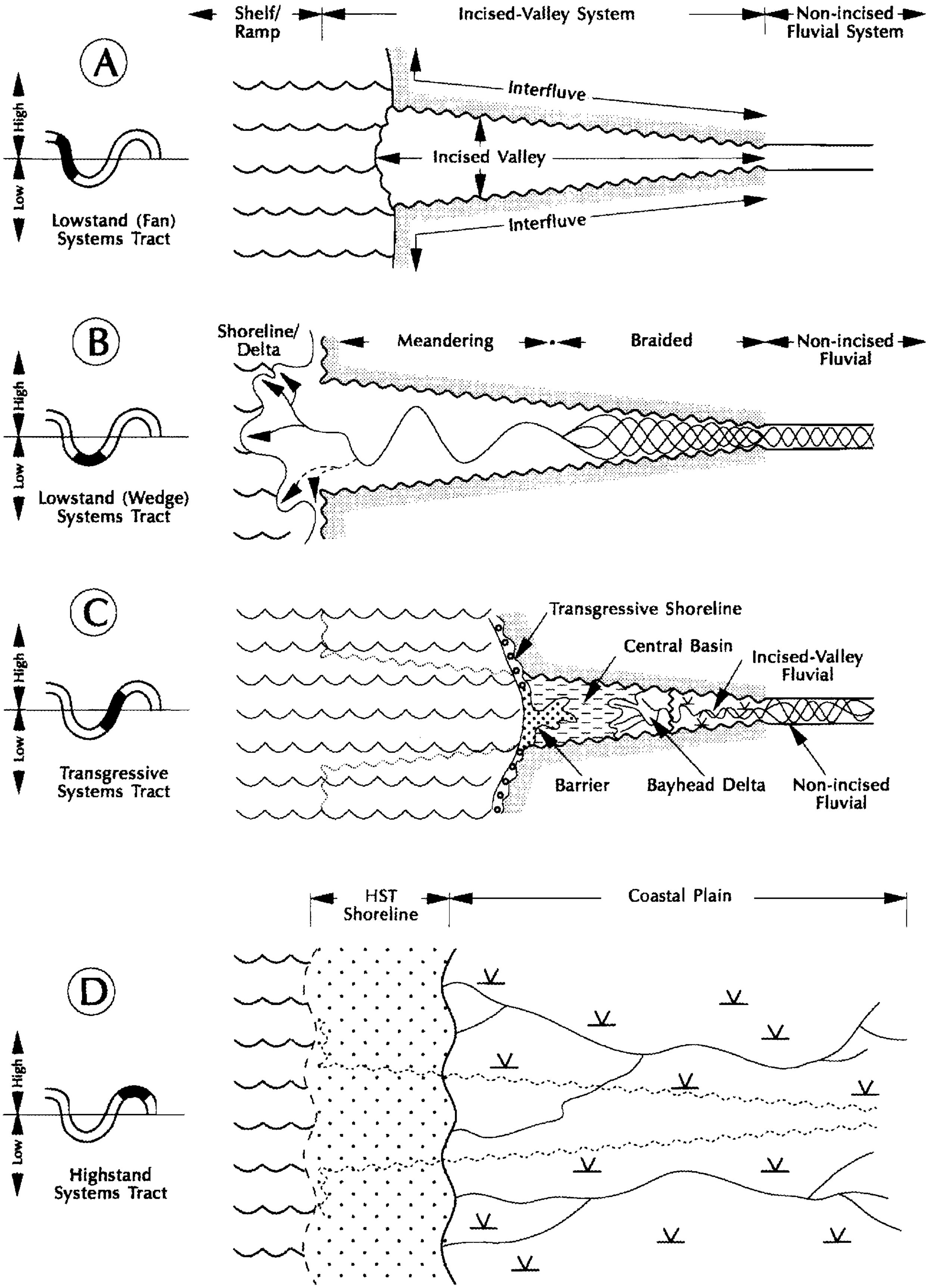
Schumm and Ethridge (this volume) and Thorne (this volume) have noted that several factors promote fluvial incision, including (but not limited to): (i) *eustatic sea-level fall* and (ii) *tectonic uplift*, both of which result in relative base-level fall (and commonly an increase in stream gradient); (iii) *climatic change* resulting in increased discharge; and (iv) *stream capture* that increases discharge in the combined system. Despite the multiplicity of causes of incision, we will limit our discussion to incised-valley systems that develop as a result of fluvial incision caused by relative sea-level fall (factors (i) and (ii) above), because such systems are associated with sequence boundaries and appear to be the most common type preserved in the geological record.

Definition

In this context, an ***incised-valley system*** is here defined as a *"fluvially-eroded, elongate topographic low that is typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base. The fill typically begins to accumulate during the next base-level rise, and may contain deposits of the following highstand and subsequent sea-level cycles."* Although exceptions may exist, incised-valley systems that occur in shallow-gradient, shelf/ramp settings typically extend landward from a lowstand delta at the mouth of the incised-valley, to a point beyond which relative sea-level change no longer influences fluvial erosion and deposition (Van Wagoner and others, 1990; Figs. 1, 2B). Above this point we consider that no incised valley (in the sense of the definition proposed above) exists; instead, a *non-incised, fluvial-channel system* feeds into the incised valley, producing a through-going fluvial network (Figs. 1, 2). In the case where sea level falls below the shelf/slope break, the incised-valley may traverse the entire shelf/ramp and transport sediment to the slope, so that the mouth of the incised valley feeds directly into a submarine canyon-fan complex (e.g., Van Wagoner and others, 1988, 1990; Posamentier and Erskin, 1991).

Fundamental Characteristics of Incised-Valley Systems

The criteria for the recognition of an incised-valley system represent the initial step in defining a generalized facies model. In light of the definition and preceding discussion, the following criteria can be identified (Fig. 3; Van Wagoner and others, 1988, 1990). (i) The valley is a negative (i.e., erosional) paleotopographic feature, the base of which truncates underlying strata including any regional markers that may be present. (ii) The base and walls of the incised-valley system represent a sequence boundary that may be correlated to an erosional (or hiatal) surface outside the valley (i.e., on the interfluve areas). This erosional surface may be modified by later transgression, forming an E/T surface (Plint and others, 1992), or a combined flooding surface and sequence boundary (an FS/SB surface; Van Wagoner and others, 1990). The sequence boundary may be mantled by a pebble lag, and/or characterized by burrows belonging to the *Glossifungites* ichnofacies (MacEachern and others, 1992; MacEachern and Pemberton, this volume). On the interfluves, the exposure surface may be characterized by a soil or rooted horizon (Leckie and Singh,


Shelf/ Ramp
Incised-Valley System
Non-incised Fluvial System
A
High
Low
Lowstand (Fan) Systems Tract
Interfluve
Incised Valley
Interfluve
B
Lowstand (Wedge) Systems Tract
Shoreline/ Delta
Meandering
Braided
Non-incised Fluvial
C
Transgressive Systems Tract
Transgressive Shoreline
Central Basin
Incised-Valley Fluvial
Barrier
Bayhead Delta
Non-incised Fluvial
D
Highstand Systems Tract
HST Shoreline
Coastal Plain

1991). (iii) The base of the incised-valley fill exhibits an erosional juxtaposition of more proximal (landward) facies over more distal deposits (i.e., a "basinward shift in facies," *sensu* Van Wagoner and others, 1990). Finally, (iv) depositional markers within the deposits of the incised-valley fill will *onlap* the valley walls.

It is critical when identifying the extent of the incised-valley system to document the geometry of the sequence boundary, both within and outside of the incised valley. The paleotopography of the incised-valley network may allow one to determine the paleodrainage direction as an aid in paleogeographic reconstruction. A variety of techniques have been employed to identify and map paleovalleys, including: (i) seismic or geological structural mapping of the erosional surface from wireline logs (e.g., Zaitlin and Shultz, 1984, 1990; Van Wagoner and others, 1990); (ii) third- or higher-order residual mapping of the erosional surface in areas affected by post-depositional structuring (e.g., Zaitlin and Shultz, 1984, 1990); and (iii) detailed isopach mapping of the interpreted fill, or of an interval between the unconformity and an overlying horizontal marker that extends over the interfluves, to locate anomalously thick sections confined to the paleotopographic lows (e.g., Seiver, 1951; Van Wagoner and others, 1990).

Piedmont and Coastal Plain Incised-Valley Systems

Incised-valley systems may reach lengths in excess of 100's of kilometers, widths to 10's of kilometers, and depths to 100's of meters (e.g., Christie-Blick and others, 1990; Leckie and Singh, 1991; Ricketts, 1991; Ashley and Sheriden, this volume). These systems may cross physiographic, lithologic and/or tectonic boundaries which may have significant affects on fluvial style (Miall, 1992; Schumm, 1993, Schumm and Ethridge, this volume), but nevertheless, two major physiographic types of incised valley occur in the stratigraphic record (Fig. 4). Incised-valley systems that have their headwaters in a (mountainous) hinterland, and that cross a "fall line" where there is a significant reduction in gradient, are here considered to be *piedmont incised-valley systems*. Incised-valley systems that are confined to low-gradient coastal plains and that do not cross a "fall line" are termed *coastal-plain incised-valley systems*.

Piedmont incised-valley systems are characterized by a longer fluvial reach than coastal-plain systems, and are commonly associated spatially with underlying structural features in the hinterland. As a result, these river systems may be longer lived than coastal-plain systems. Also, piedmont systems more commonly contain coarse-grained, immature, fluvially-derived sediment, whereas coastal-plain systems are usually filled by finer-grained and more mature deposits recycled from coastal-plain sediments. In both piedmont and coastal-plain systems, marine-derived sediment is preserved in the estuarine portion of the valley fill (see below). It is possible to have coastal-plain and piedmont incised-valley systems adjacent to each other in coastal areas (e.g., Hayes and Sexton, 1989; Fig. 4).

Simple and Compound Incised-Valley Fills

The fill of any incised-valley system may be classed as either *simple* or *compound* depending on the absence or presence, respectively, of multiple, internal sequence boundaries (Fig. 5; see Dalrymple and others, this volume). If the valley is filled completely during one lowstand-transgressive-highstand sequence, the fill is termed a "simple fill" (e.g., Rahmani, 1988; Wood and Hopkins, 1989; Fig. 5A). A "compound fill" records multiple cycles of incision and deposition resulting from fluctuations in base level, and is therefore punctuated by one or more sequence boundaries in addition to the main sequence boundary at the base of the incised valley (e.g., Clark and Reinson, 1990; Fig. 5B). Due to the presence of structural control on their location, piedmont river systems commonly exist through more than one sequence of sea-level fall and rise; thus, their incised valleys commonly contain a compound fill. Coastal-plain systems are more likely to exist through only one regressive-transgression cycle and typically have a simple fill.

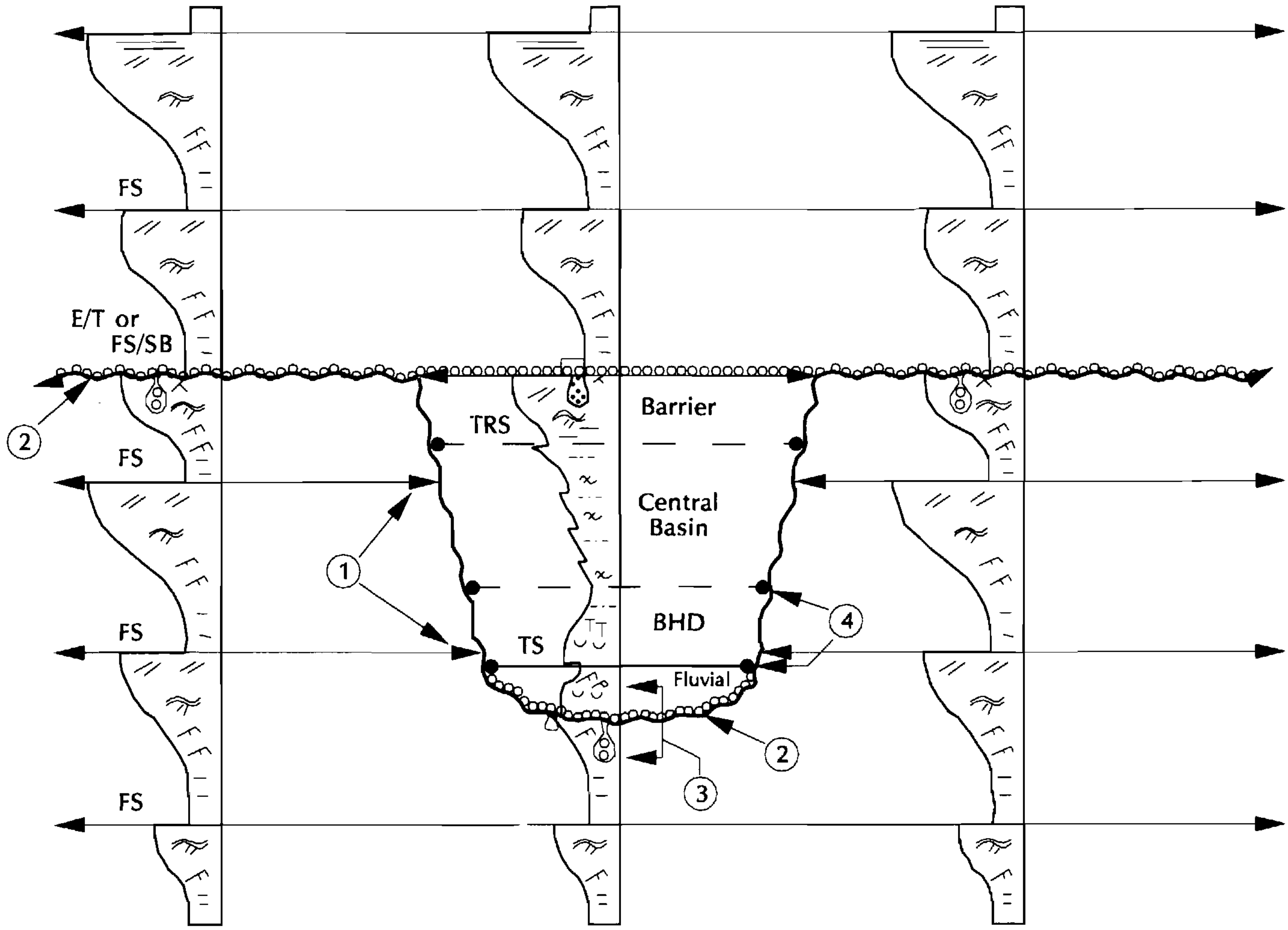
MODEL FOR A SIMPLE INCISED-VALLEY FILL

Although many incised-valley systems are characterized by compound fills (e.g., Suter and Berryhill, 1985; Suter and others, 1987; Ainsworth and Walker, this volume; Archer and others, this volume; Clifton, this volume), for simplicity and ease of discussion we will consider here the case of a piedmont incised-valley system, which is cut and filled in a single cycle of 4th or 5th order (Van Wagoner and others, 1988, 1990). We will also assume that fluvial sediment supply and the rate of transgression are constant. These assumptions will allow us to model an idealized fill without adding unnecessary complexity. We believe that, by understanding the geometry of this type of fill, it will then be easier to appreciate and predict variations in facies architecture associated with more complex, compound fills. In addition, we assume that waves are more significant than tides in the coastal zone, and that any estuaries that develop are wave-dominated (*sensu* Dalrymple and others, 1992), as this is the situation most commonly documented in ancient incised-valley systems.

Stratigraphic Organization: Overview

Following Dalrymple and others (this volume), a threefold, longitudinal subdivision is proposed for the incised-

FIG. 2.—Idealized plan view of a simple, piedmont incised-valley system showing its evolution over one complete sea-level cycle (sea-level fall to subsequent highstand). **(A)** Lowstand (fan) time showing the incised-valley system passing headward into a non-incised fluvial-channel system. The junction between the two is the knickpoint. **(B)** Lowstand (wedge) time showing a lowstand delta at the mouth of the incised valley, and the beginning of fluvial deposition throughout the incised-valley system. **(C)** Transgressive systems tract time showing development of a tripartite, wave-dominated estuarine system within the incised valley. **(D)** Highstand time with a progradational shoreface and alluvial plain that extends beyond the margins of the buried incised valley.


FS
E/T or
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2
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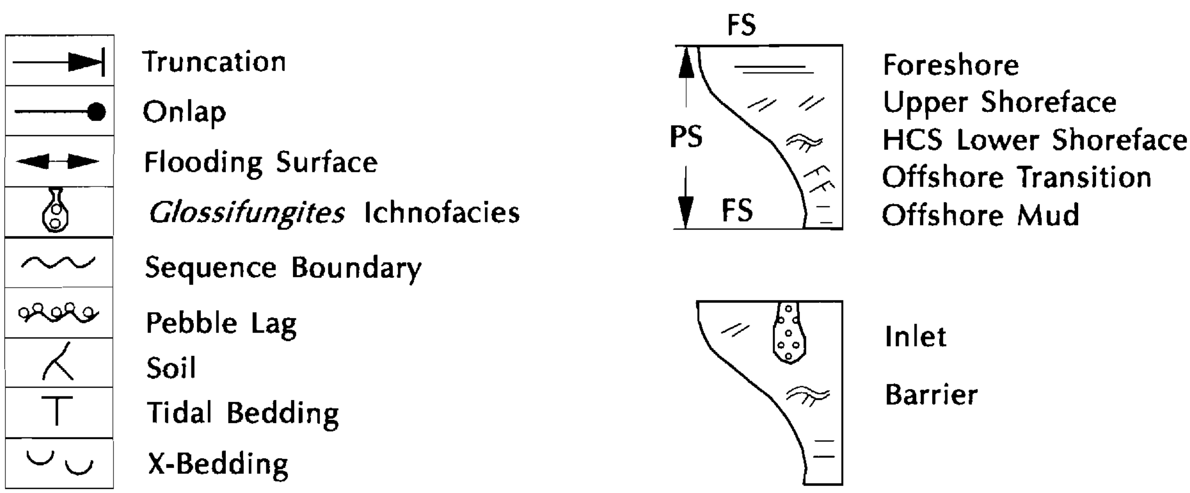
Truncation
Onlap
Flooding Surface
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Sequence Boundary
Pebble Lag
Soil
Tidal Bedding
X-Bedding
FS
PS
FS
Foreshore
Upper Shoreface
HCS Lower Shoreface
Offshore Transition
Offshore Mud
Inlet
Barrier

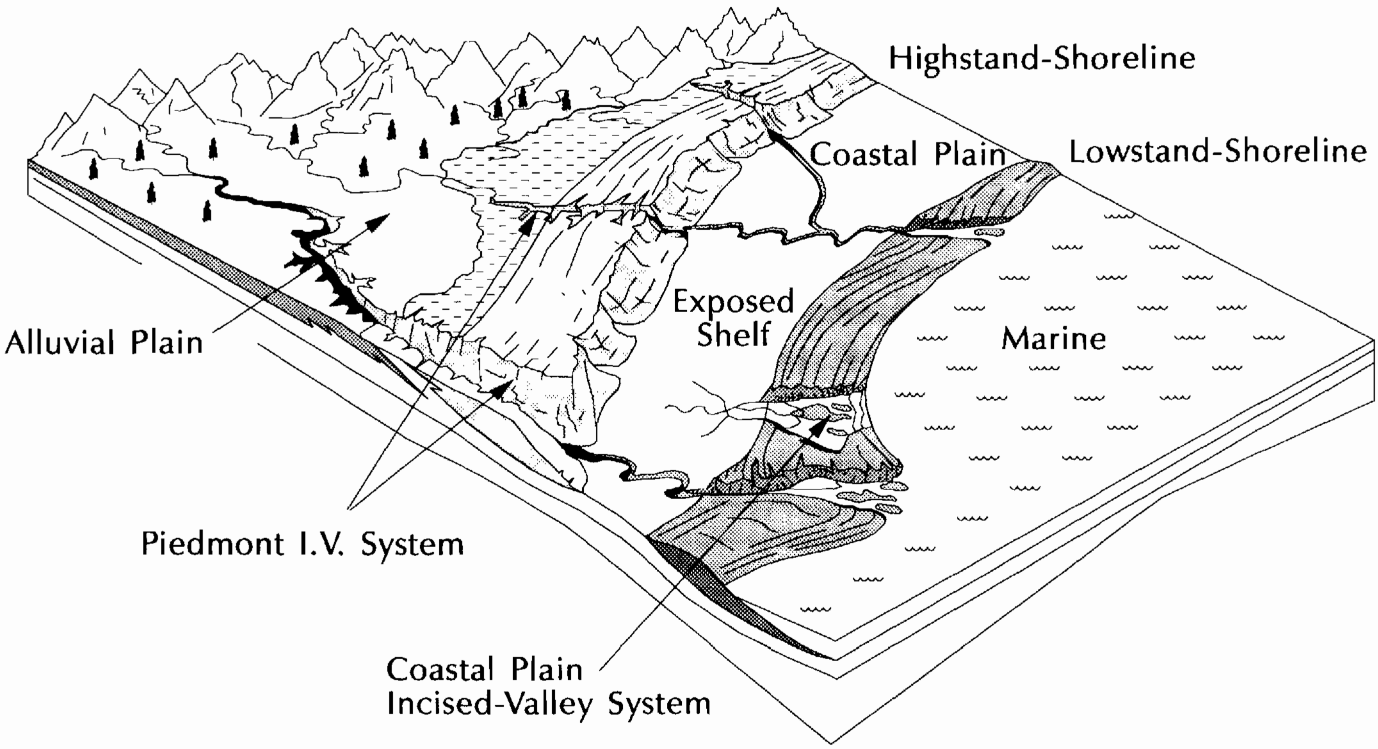


FIG. 4.—Schematic view of a coastal zone showing the distinction between piedmont and coastal-plain incised-valley systems. Modified after Rosenthal (1988) paleogeographic interpretation of the Lower Cretaceous Glauconitic Sandstone in Alberta, Canada.

valley fill (Figs. 1, 2, 6). This three-fold subdivision reflects the unique depositional/stratigraphic organization which results from transgression followed by highstand deposition.

As relative sea level falls, the entire length of the incised valley is characterized by (net) fluvial erosion which creates the basal sequence boundary (Fig. 2A). When relative sea level reaches its lowest level and starts to rise, fluvial deposition begins at the mouth of the incised-valley system (Fig. 2B), and will extend progressively further up the valley as the transgression proceeds (e.g., Belknap and others, this volume; Thomas and Anderson, this volume). It is possible, therefore, to have continuing erosion and sediment bypass in the upper (headward) regions of the incised valley as deposition is occurring in the lower (seaward) reaches during "lowstand time."

Ideally, the fill of the seaward portion of the incised-valley (Fig. 1, segment 1) is characterized by backstepping (lowstand to transgressive) fluvial and estuarine deposits, overlain by transgressive marine sands and/or shelf muds (e.g., Thomas and Anderson, this volume). The middle reach of the incised valley (Fig. 1, segment 2) consists of the drowned-valley estuarine complex that existed at the time of maximum transgression, overlying a lowstand to transgressive succession of fluvial and estuarine deposits like those in segment 1. The innermost reach of the incised valley (Fig. 1, segment 3) is developed headward of the transgressive estuarine limit and extends to the landward limit of fluvial incision (i.e., the knickpoint; Schumm, 1993). This segment is characterized by fluvial deposits throughout its depositional history; however, the fluvial style will change systematically due to changes in the rate of change of base level (Gibling, 1991; Wright and Marriott, 1993). The effect of base-level change will decrease inland until eventually climatic, tectonic and sediment-supply factors become the dominant controls on the nature of the fluvial system. The following sections will present in more detail the characteristics of each of these three segments (Figs. 1, 2, 6).

Segment 1—Outer Incised Valley

The outer incised valley (segment 1) extends from the lowstand mouth of the incised valley to the point where the

FIG. 3.—Schematic diagram illustrating the criteria for the recognition of an incised-valley system: 1—truncation of underlying regional markers by a sequence boundary; 2—regional correlation of the sequence boundary from the base of the incised valley onto the interfluves; 3—a basinward ("downward") shift in facies across sequence boundary; and 4—onlap of surfaces within the incised valley onto the sequence boundary. SB = sequence boundary; FS = flooding surface; P.S. = parasequence; E/T = surface of subaerial erosion and transgression; FS/SB = flooding surface/sequence boundary; TS = transgressive surface; TRS = tidal ravinement surface; BHD = bayhead delta; HCS = hummocky cross-stratification.

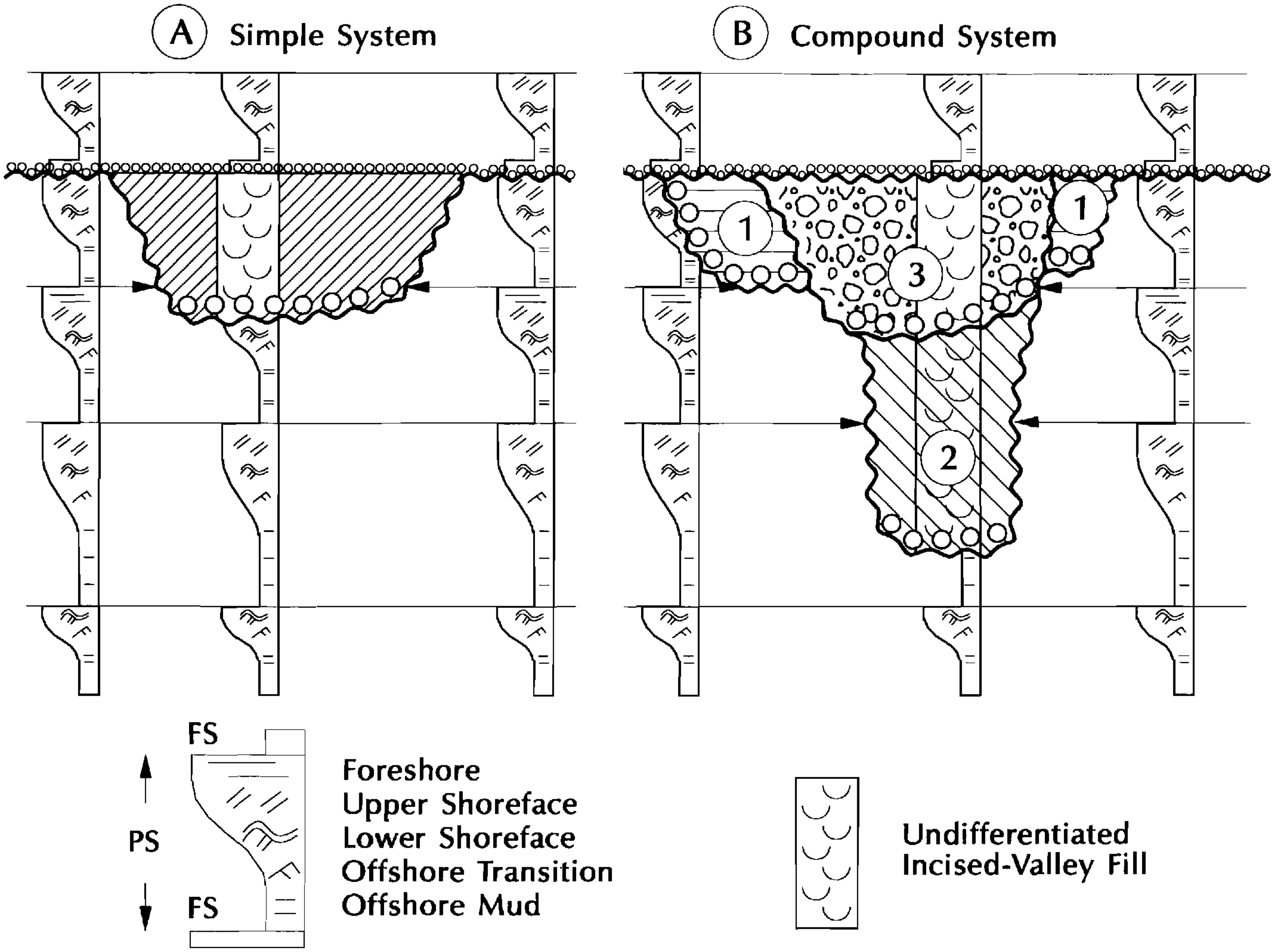


FIG. 5.—Schematic diagram illustrating (A) simple and (B) compound incised-valley systems. Numbers 1–3 refer to successive episodes of erosion and deposition within the incised valley. PS = parasequence; FS = flooding surface.

shoreline stabilizes at the beginning of highstand progradation (Figs. 1, 6). As in the other segments, this reach of the valley initially undergoes fluvial incision with the lowering of base level (Figs. 2A, B). Sediment is by-passed to the mouth of the valley where it is deposited as either a lowstand delta and/or prograding shoreline (Fig. 2B). Within segment 1, this period is represented by the sequence boundary, which may be overlain by lowstand fluvial deposits (Fig. 6, profile 1). As sea level begins to rise and the lower reaches of the system are transgressed, the incised valley changes from being a conduit for fluvially-eroded sediment, to the site of fluvial, and (subsequently) estuarine deposition (Fig. 2C). Fluvial deposition, although initiated during the late lowstand, continues during the early stages of transgression, with the locus of deposition shifting landward as relative sea level rises and the shoreline transgresses (Wright and Marriott, 1993; Wescott, 1993). Thus, the boundary between the lowstand and transgressive systems tracts (i.e., the transgressive surface) may lie within the fluvial deposits rather than at their top (cf. Allen and Posamentier, 1993, this volume).

The fluvial style (i.e., braided, meandering, anastomosed, or straight) within the incised valley is dependent on a variety of factors including the sediment supply, grain size, discharge, valley gradient, and rate of transgression (Schumm, 1977, 1993; Schumm and Ethridge, this volume). These variables will likely change during the rise in sea level associated with the marine transgression (Gibling, 1991; Wright and Marriott, 1993; Törquist, 1993). Thus, in the simplest case where all other factors remain constant, the character of the lowstand to transgressive fluvial sediments should change vertically as the depositional gradient and capacity of the fluvial system decreases as the shoreline approaches. This change would most likely result in an overall upward-fining fluvial succession, with a change from higher-energy (sandy braided?) to lower-energy (mixed sand/mud meandering?) fluvial deposits. An excellent example of this is provided by the Quaternary sediments in the Mississippi River incised valley (Fisk, 1944). Abrupt changes in style within this succession may correlate with marine flooding surfaces developed farther seaward in the valley.

The thickness of the basal fluvial succession, and the extent to which the predicted changes in fluvial style are developed, may be variable along the length of segment 1. The ultimate thickness is controlled by the accommodation space developed during the rise in sea level (Jervey, 1988), with the major factor being the ratio between the rate of fluvial-sediment input and the rate of sea-level rise. In the situation where sea-level rise greatly outpaces fluvial input, transgression is rapid, and the thickness of the fluvial deposits will be less than in the case where rapid fluvial input occurs during a slow rise in sea level. In the special case where sediment input matches sea-level rise, the fluvial deposits will aggrade vertically. In all cases, the preserved thickness of the fluvial succession may be affected by subsequent erosion associated with transgression.

As the transgression proceeds, the estuarine conditions which are established in the seaward end of the valley migrate landward. In a wave-dominated estuarine setting, the first estuarine deposits over the fluvial sediments will be *bayhead-delta* (distributary channel, levee, and inter-distributary bay) deposits (Figs. 2, 6, profile 1). Due to continued transgression, *central-basin* deposits will then overlie the bayhead delta with a gradational facies contact. The central-basin deposits will in turn be overlain by the *estuarine barrier* (cf. Boyd and others, 1992; Dalrymple and others, 1992). This contact may be gradational, but is equally likely to coincide with the erosional base of a tidal (inlet) channel. In the latter case, it is referred to as a *tidal ravinement surface* (Allen and Posamentier, 1993).

As transgression proceeds, the shoreface passes the former location of the estuary. Wave erosion associated with shoreface retreat produces a *wave ravinement surface* which will truncate the underlying estuarine deposits (e.g., Ashley and Sheridan, this volume; Belknap and others, this volume; Kindinger and others, this volume; Thomas and Anderson, this volume; Fig. 6, profile 1). This surface may then be overlain by transgressive shoreface to nearshore sands. Finally, the valley will be capped by open-marine mudstones associated with the succeeding highstand. The landward limit of these mudstones is an indicator of the inner end of segment 1.

Segment 2—Middle Incised Valley

Segment 2 lies between the inner end of segment 1 and the marine/estuarine limit at the time of maximum flooding (Figs. 1, 6); it therefore corresponds to the area occupied by the drowned-valley estuary at the end of the transgression (Fig. 2C). In this segment, the sequence boundary is overlain by lowstand to early transgressive fluvial deposits similar to those in segment 1 (Fig. 6). These are in turn overlain by transgressive estuarine facies, but in this segment the nature of the overlying estuarine succession varies along the length of the segment (cf. Dalrymple and others, 1992, their Figure 13) because the estuarine facies are (ideally) preserved with the spatial distribution they would have had in the contemporaneous estuary.

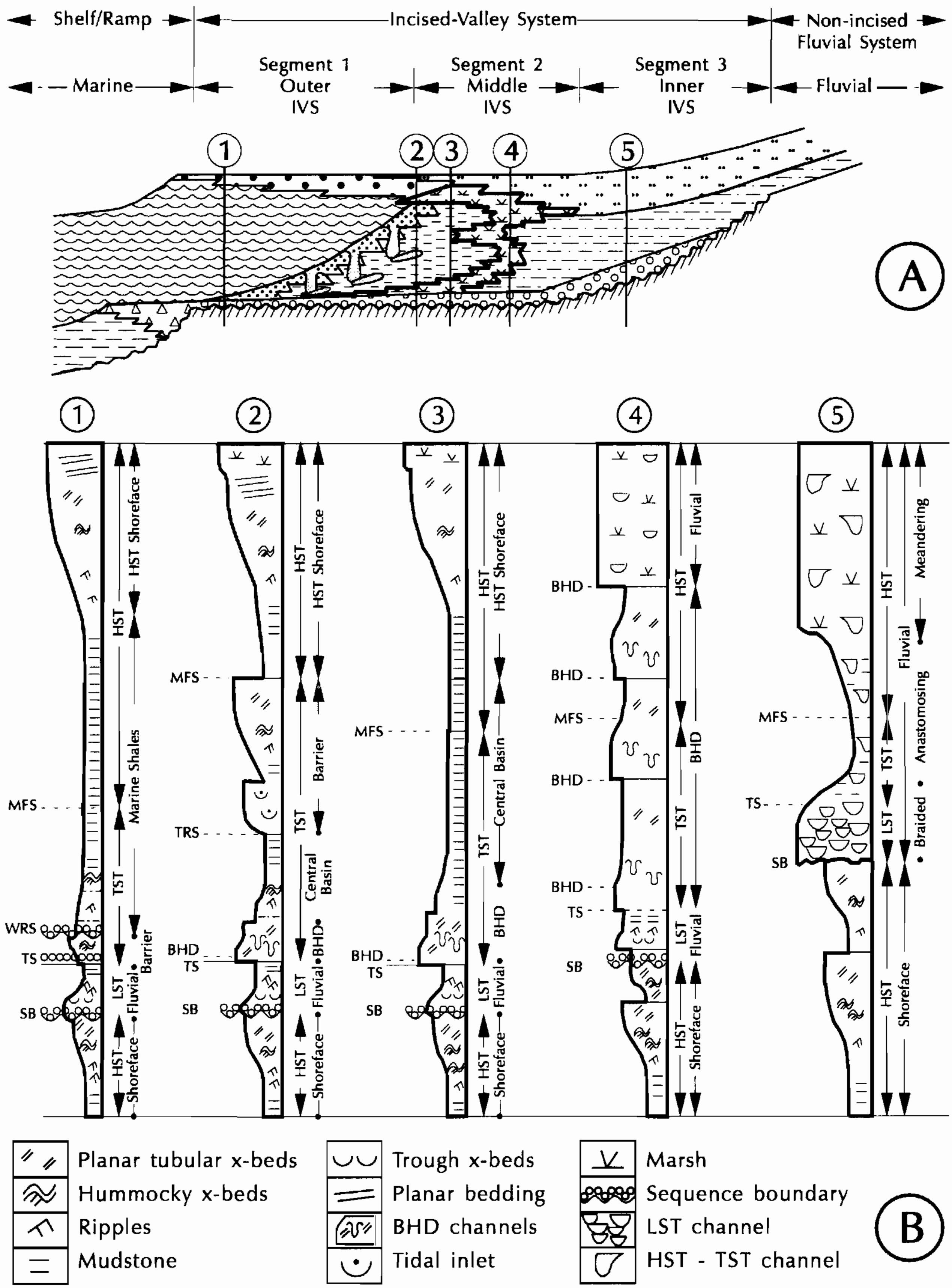
Near its seaward end, the succession is similar to that in segment 1, with bayhead-delta sediments overlain by central-basin deposits that are in turn capped by estuary-mouth, barrier sands. Because open-marine conditions do not transgress into this segment, the barrier sediments are overlain by highstand fluvial deposits (Fig. 6, profile 2). In the middle portion of segment 2, barrier sands are absent, and central-basin deposits coarsen upwards into progradational, bayhead delta and fluvial sediments of the succeeding highstand (Fig. 6, profile 3). At the headward end of segment 2, central-basin sediments are absent, and the bayhead delta is overlain directly by highstand fluvial deposits (Fig. 6, profile 4). The most landward limit of detectable marine influence (tidal features or brackish-water traces) is taken as the inner end of segment 2. This point corresponds with the inner end of the estuary as defined by Dalrymple and others (1992), and also with the "bayline" of Posamentier and others (1988) and Allen and Posamentier (1993).

Segment 3—Inner Incised Valley

The innermost segment (Segment 3) of the incised-valley system lies between the transgressive marine/estuarine limit and the landward limit of incision (Figs. 1, 2, 6). This segment may extend for 10's to 100's of kilometers above the limit of marine/estuarine influence (Shanley and others, 1992; Schumm, 1993; Levy and others, this volume). The fill of this segment will be entirely fluvial, and may be braided, meandering, anastomosed and/or straight in character, depending on a variety of factors including sediment supply, gradient, discharge, sediment size, etc.. However, relative sea-level and accommodation changes associated with the lowstand-transgression-highstand cycle influence sedimentation, and may produce a predictable vertical succession of fluvial styles (Fig. 6, profile 5; Gibling, 1991; Wright and Marriott, 1993). Lowstand fluvial deposits would be expected to be relatively thin as the fluvial system would have been erosional, or have acted as a transport conduit (a bypass zone) at that time. Late lowstand to early transgressive deposits at the base of the fill may be characterized by relatively coarse-grained, amalgamated channel deposits. As transgression proceeds, an overall upward-fining succession would be expected to develop as the gradient and stream capacity decrease. The deposits which accumulated during times of rising base level should contain more isolated, channel-sandstone bodies, interbedded with a higher percentage of overbank deposits (e.g., Törquist, 1993). Freshwater organic facies (e.g., peat or lacustrine carbonates) might be abundant and the soils less mature than those associated with the lowstand (Cross, 1988). The overlying highstand deposits may be expected to coarsen upward, due to progradation in response to decreasing rates of base-level rise and accommodation creation (Schumm, 1993).

Summary

As the foregoing idealized model illustrates, *the fill of an incised valley may be extremely complex*, even in the case where many simplifying assumptions are introduced. No single facies succession (i.e., upward-coarsening, upward-fining, blocky, etc.) occurs along the entire length of the system (Fig. 6). Data compiled by J. Barclay and F. Krause (pers. commun., 1993) suggest that transgressive successions containing estuarine deposits capped by marine shales are the most common expression of an incised-valley fill.


Shelf/Ramp
Incised-Valley System
Non-incised Fluvial System
Marine
Segment 1 Outer IVS
Segment 2 Middle IVS
Segment 3 Inner IVS
Fluvial
A
MFS
WRS
TS
SB
TRS
BHD
HST
TST
LST
HST Shoreface
Marine Shales
Fluvial
Barrier
Central Basin
Shoreface
Meandering
Anastomosing
Braided
B
Planar tubular x-beds
Hummocky x-beds
Ripples
Mudstone
Trough x-beds
Planar bedding
BHD channels
Tidal inlet
Marsh
Sequence boundary
LST channel
HST - TST channel

Possible reasons for this are: (i) segment 1, where such successions form, is longer than segments 2 and 3 in most cases and (ii) the deposits of segment 3 have not been fully recognized as incised-valley deposits.

STRATIGRAPHIC SURFACES

The infill of incised-valley systems is characterized by a number of stratigraphically-significant surfaces (Figs. 1C, 6). The surface that defines the valley form is the most regionally extensive of these. It is the *sequence boundary*, which develops through a combination of fluvial incision within the valley form and subaerial exposure of the interfluves. The specific facies expression of the sequence boundary depends, in part, on the location with respect to the valley form (see Van Wagoner and others, 1988, 1990).

In the general case, the sediments immediately overlying the sequence boundary consist of lowstand fluvial deposits. Commonly, however, a large part of the valley fill is deposited in response to rising base levels, and thus belongs to the transgressive systems tract. Consequently, the *transgressive surface*, which is defined as the flooding surface separating the progradational or aggradational, lowstand systems tract from the retrogradational, transgressive systems tract (Van Wagoner and others, 1988), should occur low in the incised-valley fill. This transgressive surface may lie within the basal fluvial deposits, especially in cases where these deposits are relatively thick (e.g., Nichols and others, this volume; Thomas and Anderson, this volume). Another important horizon low in the fill in segments 1 and 2 is the estuarine-fluvial contact, which commonly represents the first, or *initial flooding surface*. Allen and Posamentier (1993, this volume) have utilized this surface as the transgressive surface because little fluvial sediment accumulated in the Gironde valley during the rapid Holocene transgression. In the general case, however, this surface is a facies boundary (Figs. 1, 6), and has limited chronostratigraphic significance. Thus, great care is needed to define the transgressive surface within incised-valley systems.

If the transgression was intermittent, due to variations in the rate of sea-level rise or sediment supply, backstepping parasequences may be developed within the transgressive estuarine and marine portions of the valley fill in segments 1 and 2 (Thomas and Anderson, this volume). These "still-stand," progradational episodes will be separated by additional *flooding surfaces*, which may or may not be recognizable in the fluvial deposits of segment 3.

In segment 1 and the seaward portion of segment 2 of the incised valley, the next higher surface is the *tidal ravinement surface* (Allen, 1991; Allen and Posamentier, 1993, this volume; Belknap and others, this volume; "tidal-inlet diastem" of Nichols and others, this volume), which is produced by erosion in the base of the deepest tidal inlet or other tidal channel. Typically, these channels are associated with the estuary-mouth, barrier/flood-tidal-delta complex of wave-dominated estuaries, or with the sand bars and flats which extend along the length of tide-dominated estuaries. In tide-dominated shelf settings, tidal ravinement may also take place on the shelf (Dalrymple, 1992; Harris, this volume). Note that this surface is diachronous, becoming younger up the valley. Special care is needed not to confuse this surface with a fluvially-incised sequence boundary. Unlike the sequence boundary, this surface is generally confined to the incised valley (Allen and Posamentier, this volume) and cannot be correlated regionally.

As transgression continues, the *wave ravinement surface* is developed as the shoreface migrates up-system and erodes pre-existing barrier sediments (Swift, 1968), and perhaps also central-basin, bayhead-delta and fluvial deposits if wave base is sufficiently deep (Allen and Posamentier, this volume; Ashley and Sheridan, this volume; Belknap and others, this volume). Unlike the tidal ravinement surface which has a channelized morphology and is generally localized within the incised valley, the wave ravinement surface is relatively planar and of regional extent, extending over both the incised valley and the interfluves (Fig. 1). This surface is typically overlain by an upward-fining (transgressive) succession, possibly containing retrogradationally-stacked parasequences. Because the wave ravinement surface forms at the shoreface, it is only present in segment 1. It is not present in tide-dominated settings, although a tidal erosion surface formed on the shelf may take its place (Dalrymple, 1992).

The *maximum flooding surface* (MFS), which corresponds to the time of maximum transgression, is the next higher surface in the succession (Fig. 1C, 6). Its physical expression varies markedly between the three segments. In segment 1, it occurs within the marine shales which overlie the wave ravinement surface. As discussed by Loutit and others (1988), the MFS on the shelf is commonly a condensed section, with abundant biogenic carbonate, phosphate and above-normal levels of radioactive material. The MFS passes landward through the sands of the estuary-mouth barrier and initial highstand shoreline, and into the estuarine deposits of segment 2. In the central part of segment 2, it lies within the central-basin deposits where they are sandwiched between the underlying transgressive, and overlying regressive, bayhead-delta sediments (Fig. 6, profile 3). Within segment 3, the MFS may be difficult to recognize, but it may be associated with the fluvial sediments that have the most distal character and are the finest grained (Fig. 6, profile 5).

Nichol and others (this volume) and Roy (this volume) describe a *fluvial-channel diastem* (or bay-head diastem) located at the base of the distributary channels in the bayhead

FIG. 6.—(**A**) Idealized longitudinal section of a simple, incised-valley system showing the location of the schematic vertical profiles illustrated in (**B**). LST = lowstand systems tract; TST = transgressive systems tract; HST = highstand systems tract; SB = sequence boundary; TS = transgressive surface; WRS = wave ravinement surface; MFS = maximum flooding surface; FCD = fluvial channel diastem; TRS = tidal ravinement surface; BHD = bayhead delta. No particular horizontal or vertical scale intended.

delta (Figs. 1C, 6, profiles 2–4). The fluvial erosion which produces this surface can cause coarse-grained fluvial sediments to directly overlie bayhead-delta or central-basin estuarine deposits. In the extreme case, this surface can cut down through transgressive and lowstand fluvial deposits and amalgamate with, or modify, the sequence boundary. This surface may occur in the landward parts of backstepping parasequences in segment 1, or beneath fluvial deposits of the early highstand in segment 2. Channel switching may not be 100% effective in cutting down to a common level so that this surface may have significant topographic relief and limited lateral continuity. Thus, it may be difficult to correlate.

PRESERVATION POTENTIAL

Two separate issues exist when considering the preservation potential of incised-valley systems: (1) the preservation of the various facies within the incised valley and (2) the preservation potential of the incised valley itself.

In segment 1 of any incised-valley system, erosion by tidal- and wave-ravinement processes during transgression is a major control on preservation potential of transgressive estuarine and lowstand to early transgressive fluvial deposits. Scour in tidal inlets and channels may remove some or all of the underlying, transgressive, central-basin sediments, and may extend deeply enough to remove bayhead-delta and underlying fluvial deposits. In extreme cases, the tidal ravinement surface may amalgamate with the basal sequence boundary and modify it. The factors determining the depth of tidal incision are not completely understood, but it is likely that incision is greatest in mixed-energy settings such as the Gironde estuary (Allen and Posamentier, 1993, this volume); in strongly wave-dominated estuarine systems, there may be insufficient tidal energy to cause erosion, while in strongly tide-dominated estuaries a constriction is not created by waves and the tidal flow is spread over a wider area (Dalrymple and others, 1990).

Wave ravinement in segment 1 commonly removes all but the deepest portions (e.g., tidal-inlet fills) of the estuary-mouth barrier complex. The underlying deposits of the central basin, bayhead delta and fluvial system typically escape erosion in deeper valleys, provided they not been eroded previously by tidal scour, but may be removed from shallow valleys in easily-eroded, coastal-plain areas (see above). Marine erosion may also occur in tidally-dominated shelf areas (Dalrymple, 1992). For example, Harris (this volume) discusses the possibility that tidal currents have exhumed incised-valley systems, removing fluvial, estuarine and deltaic deposits, leaving the valley open, to be filled later by shelf sands and muds.

In wave-dominant settings, the preservation potential of the incised valley itself is dependent primarily on the effectiveness and depth of the wave-ravinement process during transgression (Ashley and Sheridan, this volume; Belknap and others, this volume). The depth of the incised valley relative to the depth of wave base will determine how much (if any) of the valley form will be preserved (Swift, 1968). In cases where the incised valley has been eroded into soft or semi-consolidated sediment, as is commonly the case in coastal-plain settings, it is easier for the wave-ravinement process to completely erode the incised valley. This is common in areas like the Texas Gulf Coast (Thomas and Anderson, this volume), the Louisiana coast (Suter and Berryhill, 1985, Suter and others, 1987), or the portions of the U. S. east coast that are not bedrock controlled (Ashley and Sheridan, this volume; Belknap and others, this volume). The preservation potential of incised-valley systems is greater in areas of bedrock control because the interfluves are not as easily eroded. Examples of this occur along the modern Eastern Shore of Nova Scotia (Boyd and Honig, 1992), the New England Coast (Belknap and Kraft, 1981; Belknap and others, this volume), and the coast of New South Wales (Roy, 1984, this volume). Tidal ravinement may also occur on the shelf (Dalrymple, 1992; Harris, this volume), but tidal currents are usually channelized parallel to the axis of the incised valley, as opposed to being spread uniformly along the shoreline as wave action is. Thus, tidal ravinement on the shelf tends not to obliterate valleys, and may even enhance the valley form.

In compound incised-valley fills, the multiple cut-and-fill events associated with different orders of lowstand fluvial incision are an important additional control on preservation potential (Fig. 5B). As shown by Thomas and Anderson (this volume), incised-valley systems formed by high-frequency lowstands in the early stages of an overall sea-level fall are subject to erosional removal during subsequent, lower lowstands. In comparison, preservation of paleovalley systems and their infill is enhanced during overall rising sea level, because accommodation space is being created (rather than lost). Thus, compound incised-valley fills are more likely to be preserved in low-order, transgressive systems tracts.

VARIATIONS ON THE PROPOSED MODEL

The model proposed above corresponds closely to the essential features of most simple, incised-valley systems that have been described; however, many incised-valley systems exhibit deviations from this model, as would be expected because of differing site- and time-specific factors (Walker, 1992). In this section, we will examine some of the effects of valley shape, depositional gradient, sediment supply and magnitude of sea-level change, in order to illustrate the variations that can be accommodated in the model.

Valley Shape and the Relative Influence of Waves and Tides

The shape of the incised valley has an important control on the zonation, extent and depositional style of each segment, particularly in the early stages of infilling, prior to depositional modification of the original geometry (e.g., Dalrymple and others, 1992). The shape of the incised valley may result in the amplification or damping of tidal action during transgression of the paleovalley (Salomon and Allen, 1983; Nichols and Biggs, 1985). In situations of irregular valley morphology, tidal amplification is unlikely and the estuaries tend to be hyposynchronous and wave-dominated (Dalrymple and others, 1992), with the formation of a barrier bar at a local constriction (Boyd and others, 1987). Incised-valley systems which have a more regular, funnel-shaped geometry are more likely to be hypersynchronous (Salomon and Allen, 1983) and tide-dominated (Dalrymple and others, 1992). Thus, the nature of the estuarine component of segments 1 and 2 is controlled in part by the original shape of the valley. This in turn influences the nature of the facies and stratigraphic surfaces, and the extent to which the fill escapes erosion by wave and tidal ravinement processes.

As tidal range increases, the widespread distribution of strong tidal currents may modify the shape of the incised valley to form the funnel shape which typifies macrotidal systems such as the Cobequid Bay-Salmon River Estuary (Dalrymple and Zaitlin, 1989; Dalrymple and others, 1990). During transgression, this estuarine funnel will deepen and widen, and migrate up the valley. This will be accompanied by erosion of adjacent and underlying sediments by tidal currents in the channels. As a result, the transgressing estuarine funnel will be bounded on its sides and base by a tidal ravinement surface which has a very different geometry and greater extent than the equivalent surface in wave-dominated systems.

Depositional Gradient, Sea-level Change and Sediment Supply

The length of the entire incised valley is a function of the magnitude and duration of the sea-level fall, and of the coastal-zone gradient. Large sea-level falls are more likely to take the shoreline beyond the shelf edge, thereby increasing river gradients and promoting incision. Longer-duration falls provide more time for incision and headward retreat of any knickpoint; consequently, incised valleys associated with longer falls may have a greater length than those associated with short falls. Coastal zones with steep gradients are more prone to incision than gently-inclined coastal plains (Schumm, 1993), but the coastal zone is typically narrower in the former case, and the incised valleys may be shorter than those on broad coastal plains.

The length of segment 2 is as long as the estuary which exists at the end of the transgression, which in turn is strongly dependent on the coastal-zone gradient, with longer estuaries occurring in lower-gradient settings (Dalrymple and others, 1992). The rate of fluvial sediment input, relative to the rate of sea-level rise, also has an influence, the estuary being shorter as the ability of the fluvial system to offset transgression increases. The relative lengths of segments 1 and 3 are influenced primarily by the amount of transgression (segment 1 lengthens at the expense of segment 3 as the transgression proceeds), which is in turn a function of the amount of relative sea-level rise, with larger rises producing a longer segment 1, all other factors being equal, than smaller rises.

In addition, however, the ratio between the rates of sea-level rise and fluvial sedimentation has a significant influence on the length of the segments. In the case where sediment supply by the river equals or exceeds the amount of relative sea-level rise, it is possible for the entire fill of the incised valley to be fluvial and aggradational in character. Transgression would not occur until the interfluves were inundated, and an incised-valley estuary would not be developed. Thus, the tidal and wave ravinement surfaces would not be present within the incised-valley fill, and the wave ravinement surface and transgressive surface would coincide with the top of the incised-valley system. On the other hand, if the fluvial sediment supply is small relative to the rate of sea-level rise, then there would be significant flooding of the valley and the proportion of estuarine and marine deposits in the fill would increase as the amount of fluvial input decreases. The situation shown in Figures 1 and 6, which typifies many Holocene and Cretaceous incised-valley systems we have examined, is representative of situations with relatively low fluvial input and/or a rapid sea-level rise.

SUMMARY AND CONCLUSIONS

The majority of incised valleys preserved in the stratigraphic record have formed in response either to a fall of relative sea level caused by a eustatic fall or tectonic uplift, or to an increase in fluvial discharge due to climatic change or stream capture (Schumm, 1993). Changes in discharge do not involve a change in relative sea level, and the resulting incised valleys are probably filled entirely with fluvial sediments. Relatively few incised valleys have been attributed to this cause. In contrast, many modern and ancient incised-valley systems are known or believed to have resulted from a lowering of relative sea level. Thus, in this paper, we have considered only this type of incised valley, which is, by definition, associated with the development of a sequence boundary. Such incised valleys are eroded by fluvial action during the relative sea-level fall and lowstand (Fig. 2C). Infilling commences during the late lowstand and/or early transgression, as relative sea level rises and the shoreline transgresses up the valley system. If the valley is completely filled during the transgression and succeeding highstand, the fill is here termed *simple* because it consists of a single sequence (Fig. 5A). If the valley is re-incised during one or more subsequent sea-level falls so that the fill contains two or more sequence, the fill is termed *compound* (Fig. 5B). Compound fills are more likely to occur in larger, piedmont river systems, whose position is commonly controlled by structure, than in smaller, coastal-plain systems (Fig. 4).

In a simple incised-valley fill, or in one phase of a compound fill, the incised valley can be subdivided into three idealized segments (Figs. 1, 6). The inner (landward) segment of the incised valley (segment 3) never experiences marine influence and remains fluvial throughout infilling. This segment reflects changes in relative sea level through changes in the style of fluvial deposition. The middle segment (segment 2) corresponds to the incised-valley estuary at the time of maximum transgression. Here, lowstand to transgressive fluvial and estuarine deposits are overlain by progradational (highstand) fluvial sediments. The outer segment (segment 1) of the incised valley is transgressed by the shoreline and contains a transgressive succession of fluvial and estuarine facies, overlain by marine sands and shales.

The absolute and relative length of these segments depends on a complex interaction of several variables, the most important being the particular sea-level history, the coastal-zone gradient and the rate of fluvial sediment input. The relative intensity of waves and tidal currents determines the nature of the facies, and the physical expression of the stratigraphically-significant surfaces within the incised-valley fill.

The various surfaces differ greatly in their origin, geographic extent (Figs. 1C, 6), and chronostratigraphic significance. A *sequence boundary* is present at the base of the incised valley throughout its length, and is correlative with the exposure surface on the interfluves. In situations where fluvial sediment supply is moderate to low relative to the rate of transgression, the *transgressive surface* typically lies low in the incised-valley fill. The fluvial-estuarine contact, which is commonly the *initial flooding surface*, is a diachronous facies boundary, and may not provide a useful boundary between the lowstand and transgressive systems tracts along its entire length. The stacking pattern of parasequence-scale units may be the only reliable criterion for recognizing systems tracts, especially in segment 3. In systems with mixed wave and tidal influence, two different ravinement surfaces may occur higher in the fill, but only in segment 1 and the outer portion of segment 2. Erosion by tidal currents in tidal inlets or other tidal channels creates a *tidal ravinement surface* which is typically confined to the incised valley. It could be mistaken for a second sequence boundary because it is typically overlain by coarse-grained, channel deposits. More regional erosion by waves at the retreating shoreface produces a *wave ravinement surface* that separates fluvial and/or estuarine sediment below from overlying marine deposits. Both of these surfaces are diachronous, and could become amalgamated with the sequence boundary. In the idealized case, a *maximum flooding surface* may extend throughout the incised-valley fill, passing from its typical position within marine shales in segment 1, through the center of the estuarine deposits in segment 2, into fluvial sediments in segment 3. However, rapid relative sea-level fall after the end of the transgression, or renewed sea-level rise after valley filling (but before the onset of significant progradation), may preclude development of the maximum flooding surface. Compound valley fills contain multiple sets of surfaces.

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