HISTORY OF RESEARCH, TYPES AND INTERNAL ORGANISATION OF INCISED-VALLEY SYSTEMS: INTRODUCTION TO THE VOLUME

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ABSTRACT: The study of unconformities has a long and distinguished history, and incised valleys have been recognized for more than 70 years. Early descriptions of incised-valley deposits lacked detail, with fluvial and deltaic interpretations predominating. Estuarine deposits were largely unrecognised until advances in our understanding of estuarine sedimentation permitted more sophisticated treatment of the fluvial-marine transition. Interest in incised-valley systems has increased dramatically in the last decade due to widespread application of sequence-stratigraphic concepts.

Following standard definitions, we urge that the term "incised valley" be restricted to fluvially eroded features that are larger than a single channel. A loss of accommodation space and the resulting formation of incised valleys may occur in response to factors unrelated to changes in relative sea level; however, all but one of the examples described in the volume are believed to be associated with a drop of relative sea level. Thus, the model proposed by Zaitlin and others (this volume) for this type of incised-valley system is used to group the papers according to which portion of an incised-valley system the deposits represent: *segment 1*—the portion between the mouth of the valley and the initial highstand shoreline, which is transgressed and overlain by marine deposits; *segment 2*—the region occupied by the drowned-valley estuary at the time of maximum transgression; and *segment 3*—the incised valley landward of the limit of marine/estuarine facies, which contains and is overlain exclusively by fluvial deposits. Each segment displays a predictable succession of environments and stratigraphic surfaces, but differences exist between the examples due to the poorly understood influence of such factors as the rate of sediment input and the magnitude and duration of the relative sea-level fall and rise.

INTRODUCTION

Incised-valley systems, which are considered in this volume to consist of an incised valley and its sedimentary fill, are a volumetrically minor but scientifically and economically important component of the stratigraphic record. The current interest in incised-valley fills is due in large measure to the recent popularization of sequence stratigraphy. In the Exxon version, which is the template most widely used by those working with incised-valley systems, type 1 unconformities are commonly marked by the presence of incised valleys that were eroded by fluvial action during the relative sea-level fall and lowstand (e.g., Posamentier and Vail, 1988; Van Wagoner and others, 1990). Thus, the recognition of incised-valley systems is an important criterion for the identification of sequence boundaries. As a consequence, incised-valley systems are being recognized in rapidly increasing numbers and are being found to contain significant hydrocarbon reserves (e.g., Howard and Whitaker, 1990; Van Wagoner and others, 1990; Zaitlin and Shultz, 1990; Dolson and others, 1991; Brown, 1993). At the same time, the potential for sea-level rise as a result of global warming has increased the need to understand the transgressive history of modern, drowned-valley estuaries, which serve as harbours, fisheries, waste-disposal sites and recreational areas for a significant fraction of the world's population.

The combined influence of these factors has produced a dramatic increase in research on both modern and ancient incised-valley systems. This volume is one expression of this interest. Because there has been no systematic study of incised valleys, current work lacks a conceptual framework, and case studies commonly stand in isolation. For this reason, we have gathered together in this volume a set of modern and ancient examples, in order to develop a better understanding of the complex stratigraphy of incised-valley systems.

As background to the following contributions, this introduction will review several general topics that provide a framework for assessing the relationships between the individual examples. These topics include: a review of early work on incised-valley deposits; a discussion of what does and does not constitute an incised valley, an overview of the key components of an incised-valley system, and an outline of the contents of the volume.

HISTORICAL REVIEW

Although incised-valley systems have not been studied intensely until recently, there is an extensive history of research on the subject. Prior to the development of radiometric dating, geologists were very interested in terrestrial-valley formation, because they believed that the observed rates of incision could be used to estimate the age of the earth (e.g., Lyell, 1853; Dana, 1880). Perhaps as a result of this belief, erosional unconformities have long been recognised as significant features of the rock record, and an enormous and at times deeply philosophical literature exists on their recognition, classification, and significance (e.g., Grabau, 1906; Blackwelder, 1909; Schuchert, 1927; Twenhofel, 1936; Krumbein, 1942; Shrock, 1948; Wheeler, 1958; Weller, 1960; Sloss, 1963, Weimer, 1984).

Despite this interest in unconformities, relatively little attention was directed specifically at incised valleys or their fill. For instance, erosional relief and stratal truncation, two of the key elements in the recognition of incised valleys (Van Wagoner and others, 1990; Zaitlin and others, this volume), are only two of 35 criteria listed by Krumbein (1942) as possible indicators of unconformities. Nevertheless, a brief review of North American literature indicates that ancient incised-valley systems were recognised and de-

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scribed by a number of early workers. Most of these examples appear to have been discovered in the course of regional mapping, and their descriptions are buried in geological-survey reports (e.g., Wanless, 1931a; Lee and others, 1938; Pepper and others, 1954). Relatively few were described in widely circulated journals (e.g., Wanless, 1931b; Wilson, 1948; Siever, 1951). Weller's (1960) textbook is the only one to consider incised valleys. Then as now, the impetus to document incised-valley deposits was economic, as many of the early examples were hydrocarbon reservoirs.

The three-dimensional geometry of the sediment body was of primary interest in much of this early work, with most incised-valley fills being classified as "shoestring" or "channel" sands. Indeed, some of these studies provide superb documentation of the plan geometry of the channel network, particularly notable examples being Siever's (1951) study of the geometry of the Mississippian-Pennsylvanian unconformity in southern Illinois and Pepper and others' (1954) examination of sandstone distribution in the Bedford and Berea Formations (Mississippian) of northern Ohio. By contrast, relatively little attention was paid to the depositional environment(s) in which the valley fill accumulated. In many instances, "channel sand" was deemed sufficient. In addition, little effort was made to distinguish between channels in an unbroken progradational succession and incised valleys formed in response to a base-level fall (e.g., Wanless and others, 1970) In almost all cases where a specific environment was suggested, the valley fill was treated as a single, undifferentiated entity. Prior to the 1970's, fluvial (e.g., Siever, 1951; Stokes, 1961; Harms, 1966) and deltaic (e.g., Pepper and others, 1954; MacKenzie, 1965) interpretations predominated due in part to the influence of Fisk's (1944; Fisk and others 1954) seminal work on the Mississippi River incised valley and delta. In the case of deltaic interpretations, the confined nature of the deposits led to some unrealistic paleogeographic reconstructions (Fig. 1).

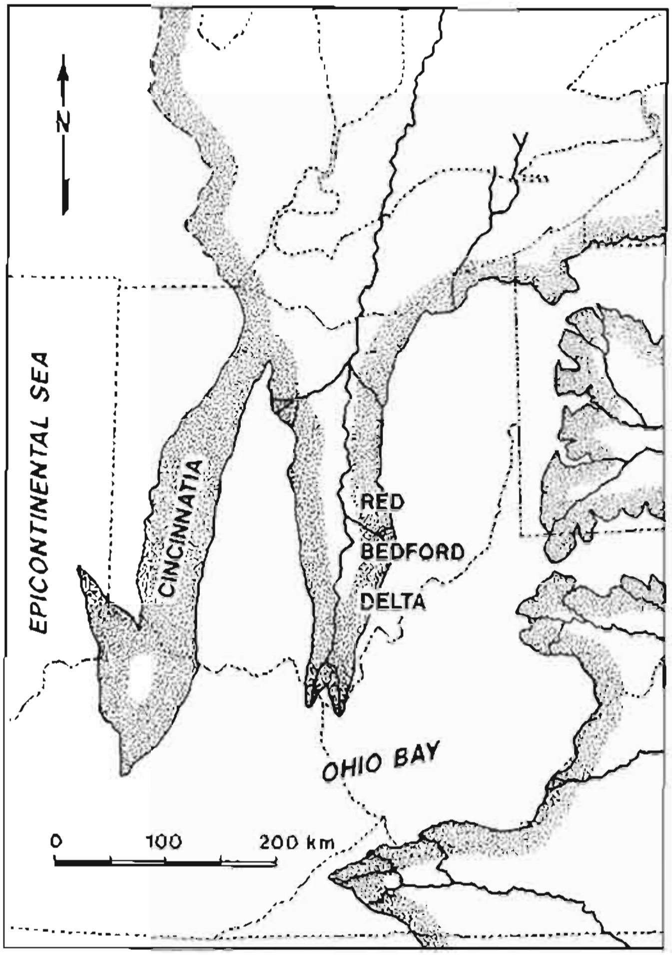

FIG. 1.—Paleogeographic reconstruction of northern Ohio during middle Bedford Shale (Early Mississippian) time. Failure to fully appreciate the incised-valley setting of the unit has led to the unrealistically elongate form of the inferred "Red Bedford Delta." The areas shown as submerged on either side of the delta were probably emergent during deposition of the "channel sands." After Pepper and others (1954, Plate 13C).

One of the notable exceptions to the foregoing is Wilson's (1948) description of Upper Ordovician, valley-fill deposits in Tennessee. Based largely on paleocurrent information, he proposed that the sediment moved up-valley from a marine source and inferred a tidally-influenced, estuarine origin for the fill (Fig. 2). Although aspects of this interpretation are open to question (e.g., why there are no fluvial deposits in a fluvially-cut valley), the reconstruction is very modern in appearance and is easily reinterpreted in sequence-stratigraphic terms (Fig. 2). For many years, however, this remained one of the few estuarine interpretations of an incised-valley fill.

From the mid 1960's to early 1980's, the focus of sedimentological research moved away from stratigraphic studies and concentrated instead on the development of "static" facies models (Walker, 1992), which emphasised the role of autocyclic processes and largely ignored the influence of relative sea-level changes. Perhaps as a result, there are fewer studies of incised-valley systems from this period. The publication of American Association of Petroleum Geologists Memoir 26 (Payton, 1977) and subsequent elaboration of the Exxon school of sequence stratigraphy (e.g., Wilgus and others, 1988; Van Wagoner and others, 1990) fundamentally changed the focus of research and ushered in the current phase of work on incised-valley deposits. Throughout the history of incised-valley research, valley incision has generally been ascribed to a drop in relative sea level, but this interpretation has become more explicit in the last fifteen years.

At the same time, our ability to recognize estuarine deposits, which are an important component of many incised-valley systems, took a large step forward. At the small scale, Visser (1980) demonstrated the existence of tidal bundles and neap-spring cyclicity in cross-bedded sands, thereby providing a means of recognizing the tidal signature that characterizes many estuarine deposits. On the large scale, Roy and others (1980) and Roy (1984), following earlier work by Oomkens and Terwindt (1960), Allen and others (1970), Nelson and Bray (1970), and Reinson (1977) popularised the now widely-used, tripartite facies model for wave-dominated estuaries. This model, which was the first to encompass the entire length of an estuarine system, has since been extended to all estuaries (Dalrymple and others, 1992). Studies by Kraft and associates (e.g., Kraft and others, 1973;

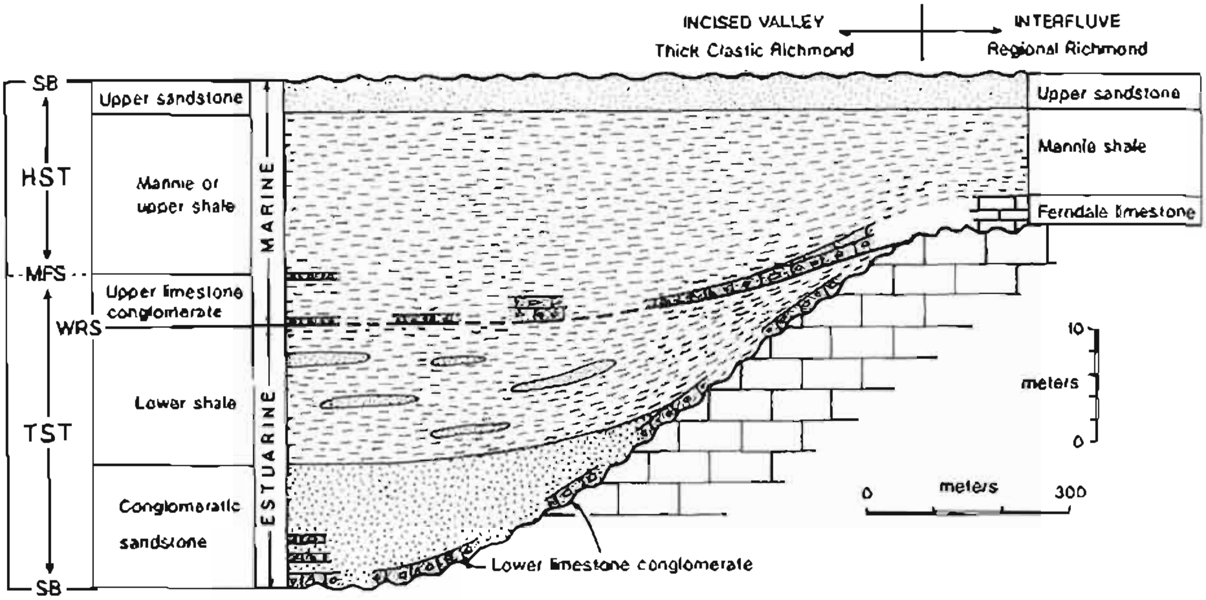

FIG. 2.—Diagrammatic cross section showing distribution of facies and depositional environments within a late Ordovician incised valley, central Tennessee (after Wilson, 1948, Fig. 3), with the inferred sequence-stratigraphic interpretation (left margin). SB = sequence boundary; TST = transgressive systems tract; HST = highstand systems tract; WRS = wave ravinement surface; MFS = maximum flooding surface. The Mannie shale thickens over the valley due to differential compaction and remaining (unfilled) relief. The inferred absence of fluvial sediments at the base is intriguing, and it may be that parts of the Lower limestone conglomerate and Conglomeratic sandstone are lowstand to transgressive fluvial deposits. The position of transgressive surface is unclear.

Belknap and Kraft, 1985; Kraft and others, 1987) in Delaware estuaries provided important information on the stratigraphic organisation and preservation potential of estuarine facies in transgressive settings.

The first application of the tripartite model to preserved deposits appears to have been by Nelson and Bray (1970) in their description of Holocene valley-fill sediments in the ancestral Sabine River on the Texas shelf (see Nichol and others, and Thomas and Anderson, this volume, for further discussion of this area). More recently, Rahmani's (1988) work on an incised-valley deposit in the Cretaceous of Alberta did much to bring this model to widespread attention (see Ainsworth and Walker, this volume, for a new look at this unit). Numerous estuarine deposits have now been documented, many of them comprising portions of incised-valley systems (e.g., Zaitlin and Shultz, 1984, 1990; Reinson and others, 1988; Howard and Whitaker, 1990; Leckie and Singh, 1991; Ricketts, 1991).

As the number of documented incised-valley deposits has increased in the last few years, significant variability has emerged with respect to the facies present and their stratigraphic complexity. For example, some incised valleys contain no fluvial sediment at their base (the fill is entirely estuarine and marine), despite the inference that the valley was cut by rivers (e.g., Reinson and others, 1988; Pattison, 1991), while others are largely to entirely filled with fluvial deposits (e.g., Dolson and others, 1991; Shanley and McCabe, 1991). Some valleys are filled by a single depositional sequence (defined as a *simple fill* by Zaitlin and others, this volume), whereas others are interpreted to contain multiple sequences (a *compound fill*). Organising the flood of new observations into a unified model or models will be a key challenge of future research. The important elements of one such model are discussed briefly below, but before doing this, it is necessary to examine the range of features which might be considered as an incised valley. Only by restricting discussion to a clearly-defined set of features with a common origin will it be possible to develop a model that depicts the anticipated stratigraphy accurately.

TYPES OF INCISED VALLEY

It follows from the common definition of "valley" (e.g., Gray and others, 1972) that incised valleys are elongate erosional features that are larger than a single channel. It is also explicitly stated in most definitions that the erosion is caused by rivers. This concept is implicit in all of the papers in this volume (with glacial modification in some cases) and is an overriding theme in previous work on incised valleys.

It does not follow, however, that all fluvially eroded valleys have equal stratigraphic significance. Indeed, two fundamental classes of incised fluvial valleys should be recognized: (1) those which are eroded in response to a fall of relative sea level (i.e., due to a eustatic sea-level fall or tectonic uplift of the coastal zone); and (2) those which are not related to relative sea-level change (i.e., erosion is due to tectonic uplift of an inland area, or to an increase in fluvial discharge caused by climatic change; Schumm and others, 1987; Blum, 1992).

Incised valleys belonging to the first class are associated with sequence-bounding unconformities (*sensu* Van Wagoner and others, 1990), and are influenced by marine processes along some of their length. Most previously described incised valleys, modern and ancient, including all but one example in this volume (Fraser, this volume), are either inferred or assumed to belong to this category. Thus, most papers in this volume implicitly or explicitly (see Zaitlin and others, this volume) define an *incised-valley system* as consisting of: (1) an erosional valley, which is formed by river action during a relative sea-level fall; and (2) the valley fill, which may begin to accumulate near the end of the lowstand, but which typically contains sediments deposited during the succeeding base-level rise. Deposits of the following highstand and subsequent sea-level cycles may also be present within the fill. It is inherent in this definition that the valley is larger than a single channel and that the erosion surface has regional extent. The basal deposits of the fill should (ideally) show an abrupt seaward shift of facies relative to those beneath the erosion surface (Van Wagoner and others, 1988, 1990; Zaitlin and others, this volume). In this type of valley the fill typically contains a complex assemblage of fluvial, estuarine, deltaic and fully-marine facies; however, as discussed briefly below (see also Zaitlin and others, this volume), these deposits have a predictable organisation due to changes in accommodation space during infilling.

Although incised valleys in the second class are also common at present, few workers have studied them (e.g., Blum, 1992; Fraser, this volume), and valleys of this type have not been widely identified in older successions. Indeed, their recognition may be difficult, as they are likely to occur within fluvial successions and to be filled by terrestrial deposits. Unlike those of the first category, such incised valleys have no sequence-stratigraphic significance in the sense of Van Wagoner and others (1990). Nevertheless, systematic changes in fluvial style may occur during filling, due to cyclic changes in accommodation space caused by tectonics and/or climate. Further work is needed to determine the characteristics and abundance of this type of incised-valley fill.

In ancient successions, many features which do not fall into either of the above categories may be confused with incised valleys. Erosionally based, fluvial-channel deposits that have the dimensions of a single channel (10's to many 100's of meters wide and up to 10+ m deep) should not be classified as an incised valley, as they typically result of autocyclic processes such as channel avulsion, stream capture, or normal coastal progradation (Van Wagoner and others, 1990; Schumm, 1993). Thus, they do not imply regional changes in accommodation space. Tidally-eroded features, including shore-normal, tidal-inlet scours (the tidal ravinement surface of Allen, 1991 and Allen and Posamentier, 1993), also rarely fulfill the definition of a valley. In most cases, they form in response to an increase (not a decrease) in accommodation space, and although they are commonly associated with a fluvially produced valley (Allen and Posamentier, this volume; Ashley and Sheridan, this volume), they need not be. The Schelde estuaries in The Netherlands, which were created by tidal scour during the Holocene transgression and captured the Schelde River (Zagwijn, 1986; P. Vos, pers. commun., 1992), are an example of this. Similarly, shelf-edge canyons and gulleys formed by slumping and mass flows should not be classified as incised valleys because they may not be associated with a fluvial system and need not be linked to changes in relative sea level (e.g., Jansen and others, 1987; Bouma and others, 1992). Therefore, great care must be taken before an incised-valley origin is ascribed to an elongate erosional feature.

INCISED-VALLEY SYSTEMS ASSOCIATED WITH RELATIVE SEA-LEVEL CHANGES

As indicated above, all but one of the case studies in this volume deal with incised valleys caused by a fall of relative sea level. Despite this, the examples are extremely diverse in terms of the nature and stratigraphic organization of the facies within the valley fill. Zaitlin and others (this volume) have attempted to synthesize these studies and previous descriptions into a general model for this type of incised-valley system. This model provides a framework which helps to integrate the described examples; therefore, we have used it to organize the contributions into groups with similar depositional settings. As background to what follows, we briefly summarise the main elements of the model here. Readers are referred to Zaitlin and others (this volume) for details.

The model is developed for a simple incised-valley system, in which the valley is cut during a single, relative sea-level fall and fills completely during the ensuing transgression and highstand. Thus, the fill consists of a single depositional sequence, such as might be formed in a relatively small valley during a high-frequency, sea-level cycle.

Erosion of the valley will be initiated in the region exposed by the relative sea-level fall, and incision will propagate headward with time. If the lowstand is relatively short, incision will not extend all the way to the mountainous hinterland, and the incised valley will pass landward into a non-incised fluvial system that is not influenced by the base-level fall (cf. Schumm and others, 1987; Schumm, 1993). During the subsequent base-level rise, fluvial sediment supply is commonly less than the rate of creation of accommodation space, and a drowned-valley estuary is generated at the seaward end of the incised valley. This estuary and its associated shoreline migrates landward throughout the transgression, stabilizing only as the rate of relative sea-level rise decreases to zero at the beginning of the next highstand. From this time on, fluvial and marine sediment input leads to deltaic or coastal-plain progradation, such that highstand deposits fill any remaining space within the incised valley.

Based on this succession of events, Zaitlin and others (this volume) identify four key points along the length of an incised valley (Fig. 3): (1) the seaward limit of the incised valley, which corresponds approximately with the landward limit of the lowstand wedge; (2) the seaward limit of the estuary at the time of maximum transgression, which corresponds with the shoreline position at the beginning of the highstand; (3) the landward limit of marine influence (the landward end of the estuary; Dalrymple and others, 1992) at the time of maximum transgression; and (4) the landward limit of incision during the lowstand.

These points in turn define three valley segments, each of which experiences a different depositional history and has a distinct stratigraphy (Fig. 3; Zaitlin and others, this volume, Fig. 6; see also Dalrymple and others, 1992, Figs.

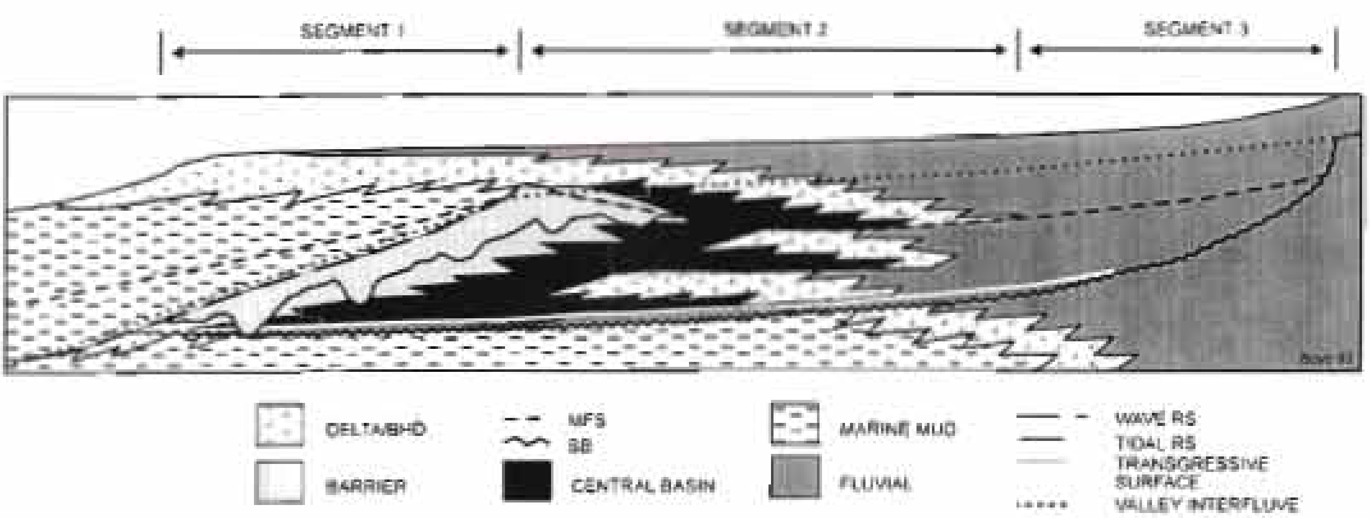

FIG. 3.—Diagrammatic section along the length of an incised valley, showing the valley segments, facies, and surfaces comprising an idealized, simple, incised-valley system. Great vertical exaggeration, but no particular vertical or horizontal scale implied. See text and Zaitlin and others (this volume) for further discussion.

13, 14). The most seaward portion (*segment 1*) initially experiences fluvial and estuarine deposition, but is transgressed by the shoreline so that the estuarine deposits are overlain by marine sediments. The middle portion (*segment 2*) of the valley is the zone occupied by the drowned-valley estuary at the time of maximum transgression. The lower part of the valley fill consists of a transgressive, fluvial to estuarine succession like that in segment 1, but is overlain by a progradational, estuarine to fluvial succession which accumulates as the estuary fills at the beginning of the highstand. The most landward portion of the valley (*segment 3*) lies beyond the limit of estuarine/marine influence. It remains fluvial throughout its history, and is overlain by terrestrial deposits. The extent to which the changes in base level are reflected in the facies of the fluvial fill of this segment depends on river gradient and distance from the marine limit, with the base-level signal decreasing in strength inland (e.g., Blum, 1992). The relative lengths of these three segments will vary from example to example (cf. Zaitlin and others, this volume), but segment 2 is likely to be the shortest of the three (although it could be tens to hundreds of kilometers long: Dalrymple and others, 1992).

Because the incision is caused by a relative sea-level fall, the basal erosion surface represents a *sequence boundary*. The assignment of the overlying valley fill to systems tracts is scale dependent. In work pertaining to thick, low-frequency sequences, the entire valley fill was placed in the lowstand systems tract (e.g., Van Wagoner and others, 1988). In the model (Fig. 3), by contrast, the fill contains sediments belonging to the lowstand, transgressive and highstand systems tracts of a high-frequency sequence. Consequently, the *transgressive surface* and *maximum flooding surface* are present within the fill (Allen and Posamentier, this volume; Zaitlin and others, this volume), although they may not be easily identified. Erosional surfaces produced by the tidal inlet and associated channels at the mouth of the estuary (the *tidal ravinement surface*, Allen, 1991) and by fluvial channels at the head of the estuary (the *bayhead diastem*, Nichol and others, this volume) are likely to be more prominent, and care is needed not to confuse them with sequence boundaries. A *wave ravinement surface* produced by landward retreat of the shoreface (Swift, 1968) marks the top of the estuarine deposits in segment 1 of wave-dominated and mixed-energy settings.

No generalized model can reflect the variability that exists between real examples. However, the above model (Fig. 3) provides a basis that makes it possible to identify several of the more significant causes of variation.

1. The model developed by Zaitlin and others (this volume) emphasises the allocyclic controls on sedimentation, because they determine the basic organisation of the deposits. The nature of the individual facies and the expression of the various surfaces are determined, however, by environmental variables such as the relative intensity of waves, tides and river currents (Coleman and Wright, 1975; Dalrymple and others, 1992), alluvial-plain gradient, and sediment grain size (cf. Orton and Reading, 1993).
2. The relative amounts of fluvial and estuarine facies depend on the rate of sediment supply by fluvial and marine processes, relative to the rate of transgression. Thus, the thickness and proportion of fluvial deposits in segments 1 and 2 will increase as the rate of fluvial sedimentation increases and the rate of relative sea-level rise decreases. It remains to be determined, however, whether the absence of fluvial deposits in features interpreted as fluvially-cut valleys (e.g., Fig. 3; Wilson, 1948; Rahmani, 1988; Pattison, 1991; Ainsworth and Walker, this volume) can be accounted for by rapid transgression and a low rate of fluvial sedimentation. Such an explanation appears appropriate for small tributary valleys (Ashley and Sheridan, and Belknap and others, this volume) but is less likely in larger trunk systems (Colman and Mixon, 1988; Ashley and Sheridan, this volume).
3. The stratigraphic complexity of the valley fill, including the number of parasequences in a simple fill or of se-

segment. The small number of examples of segment 3 (fluvially filled valleys in a fluvial succession) is perhaps surprising, as one might expect this valley segment to be of considerable length. Whatever the reason, this valley segment is the least well documented of the three and deserves further study.

Finally, simple fills slightly outnumber compound fills in the examples documented in this volume, but further work is needed to determine whether this is a valid generalization. Many more examples of compound fill must be described before the factors controlling their distribution become clear.

CONCLUDING STATEMENT

The study of incised-valley systems is one of the major outgrowths of sequence stratigraphy, and significant advances in our knowledge of these complex environments have occurred over the last ten years. Nevertheless, our understanding remains imperfect. Because incised-valley systems are a direct response to cyclic changes in accommodation space, any facies model(s) which may be developed will differ conceptually from earlier, static facies models in which the organisation is imparted largely by fluid-mechanical processes. Although the framework for a model is beginning to emerge for incised valleys created by relative sea-level falls, the relative importance of the many allocyclic and autocyclic factors which influence incised-valley sedimentation remain poorly known. Furthermore, almost nothing is known about other types of incised-valley deposits. Hopefully the contributions in this volume will provide the stimulus for further systematic study.

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