A REVIEW OF NON-MARINE SEQUENCE STRATIGRAPHY

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Introduction

There has been a virtual explosion of stratigraphic studies utilizing the principles of sequence stratigraphy recently. Although the concept of time stratigraphy is not new, the packaging of depositional units into system tracts and sequences is. Sequence stratigraphy has evolved from the original concepts of seismic stratigraphy to a scale above seismic resolution. This concept provide a greatly improved understanding of facies geometries and reservoir architecture. It has developed into a powerful predictive facies analysis tool for both the hydrocarbon industry and academic research. This new approach has led to the reassessment of areas that in some cases have been the subject of intense geological scrutiny for decades.

Most sequence-stratigraphic research has concentrated on shallow marine and marginal-marine strata. However, one of the most controversial aspects of sequence stratigraphy is how relative sea-level changes influence non-marine depositional environment. Posamentier and Vail (1988) used the accommodation models of Jervey (1988) to develop conceptual models that relate fluvial deposition to the changes in relative sea-level assuming a constant sediment influx. These conceptual models have been criticized for being oversimplistic on a variety of scales (e.g. Miall, 1991 and Shanley & McCabe, 1994). In general, parasequences are not identifiable within alluvial strata (Aitken & Flint, 1994). Thus, other criteria are used to define system tracts and their bounding surfaces, for example coal-bearing stratas to infer maximum flooding surfaces (e.g. Cross, 1988 ; Aitken & Flint, 1994).

Basic Philosophy

Sequence stratigraphy is the study of the rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities (Van Wagoner, 1990). The essential unit of sequence stratigraphy is the sequence, which is a rock unit bounded by unconformities and their correlative conformities. A sequence can be subdivided into system tracts, which are defined by their position within the sequence and by stacking patterns of parasequence sets and/ or parasequences bounded by flooding surfaces. Boundaries of sequences, parasequence sets and parasequences provide a chronostratigraphic framework for correlating and mapping sedimentary rocks.

One way to augment sequence stratigraphic analysis where variations in accommodation and sediment supply have to be understood is by analyzing cyclic patterns. It is a common observation that coastal and shelf deposits are organized into cyclic patterns at various scales. These cycles have been studied by numerous sedimentologists since the beginning of the century and various mechanisms have been proposed for their formation (see Einsele, 1992).

Some authors have pointed to limitations in current sequence stratigraphic models for river deposits (e.g. Miall, 1991; Wright & Marriott, 1993; Shanley & McCabe, 1994). One of the main problems is that, at present, it is difficult to describe alluvial sediments in sequence stratigraphic terms without first interpreting whether they may, for example, have developed during a rise or a fall in relative sea-level. Interfluvial sequence boundaries are the correla-

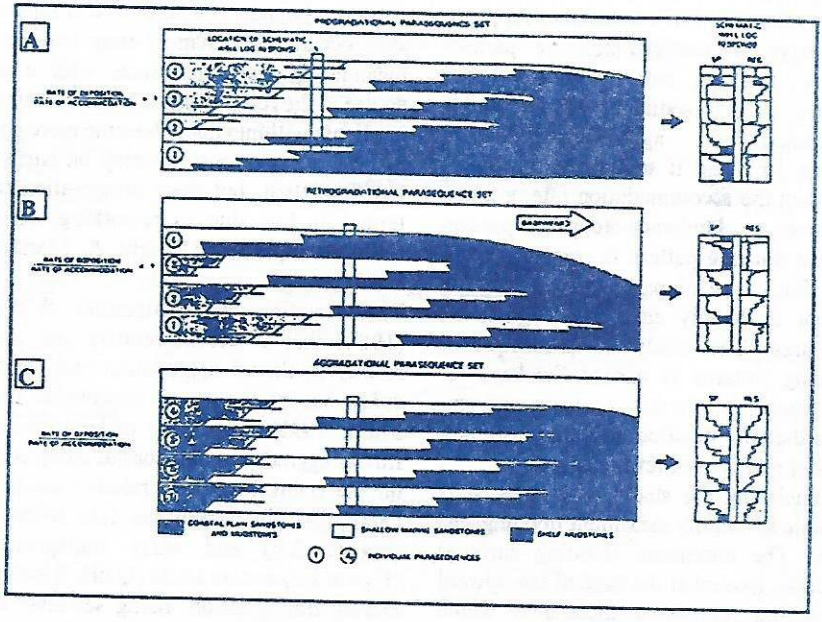


Figure 1: Parasequence stacking patterns in response to sediment influx (rate of deposition) and rate of accommodation (from Van Wagoner et. al., 1990)

tive conformities to type 1 sequence boundaries and are one of the most difficult surfaces to recognize.

The other aspect in fluvial environments is the principle which controls sedimentation where a stream will aggrade if its equilibrium profile shifts basinward or upward and incise if its equilibrium profile shifts downward. In the Exxon version, the downward shifts will result a type 1 sequence boundary which is commonly marked by the presence of incised valleys that were formed by fluvial incision during the relative sea level fall and lowstand. Incised-valley-systems 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.

Stacking Patterns

The concept of sediment accommodation is of primary importance in understanding stacking patterns and reservoir continuity in alluvial and shelf depositional environments. Variations in the rate of change of sediment accommodation is one of the key factors which determine sedimentary stacking patterns.

The primary parameter controlling the overall stacking patterns of deltaic deposits, for example, is the rate at which space is created on the shelf to accommodate continuous deposition. The resulting stacking pattern is a function of the ratio between the overall rate of sediment influx and the rate of creation of space available or accommodation. Variations in both parameters result in three different types of parasequences stacking pattern (Van Wag-

oner et. al. 1990).

If accommodation increases slowly relative to the volume of fluvial sediment supply, a regressive or seaward-stepping parasequence stacking pattern is developed (Figure 1.a). If sediment supply equals accommodation, aggradation occurs (Figure 1.c), and if sedimentation rate is less than the accommodation rate, a transgressive or landward-stepping parasequence stacking pattern is created (Figure 1.b). Each type of parasequence stacking pattern is usually easy to recognize on well-logs. The study of parasequence stacking patterns is one of the keys for sequence stratigraphic analysis and enables the identification of larger-scale patterns of relative sea level change.

By analyzing the stacking patterns, it is possible to identify maximum flooding surfaces. The maximum flooding surfaces would be located at the base of the upward coarsening regressive succession which overlies earlier landward-stepping parasequence stacking pattern.

Non-marine Sequence Stratigraphy

The sequence stratigraphic models developed for sequences by Posamentier and Vail (1988) identify two types of sequences for clastic deposition. When the rate of subsidence is relatively low, a type 1 sequence boundary occurs, characterized by stream rejuvenation and incision. A type 2 sequence boundary is associated with higher rates of subsidence; no stream incision occurs and therefore there is no unconformity.

In the lowstand system tract, fluvial deposits may appear in marginal marine sequences, but such events are more likely to cause termination of fluvial deposition and reworking in the main fluvial system. Following a type 1 sequence boundary with incision and valley formation, mature and well-drained soils develop on terraces or interfluves (Figure 2.a). Their potential for preservation depends on the rate and nature of the transgression. While on a type 2 sequence boundary, where little or no incision occurs, the channel may resume a meandering platforms since, with a decrease in the relative sea-level fall, channel gradients will inevitably become more gentle. Mature soils may develop on parts of the floodplain, but their preservation potential is low due to reworking during channel migration (Wright & Marriott, 1993).

The assertion by Posamentier & Vail (1988) that a fall in relative sea level results in fluvial aggradation and coastal onlap has shown to be improbable (e.g. Miall, 1991). It is now understood that fluvial aggradation and coastal onlap occur on the rising limb of a relative sea-level curve, that is during the late lowstand (Figure 2.b) and early transgressive (Figure 2.c) system tracts (Quirk, 1996).

During transgression, rising sea-level has two effects on the fluvial system. Firstly, as base-level raises, accommodation space is created, allowing fluvial aggradation. However, some authors (e.g. Allen & Posamentier) do not think that fluvial aggradation occurs in transgression. Secondly, the frequency of flooding in the rivers increases (Wright & Marriott, 1993), leading to higher rates of vertical accretion. This will affect the channels units to be relatively isolated from one to another with low interconnectedness (Allen, 1978). This change can be detected in the well-logs by analyzing the stacking patterns. However, if the rate of base-level rise is relatively slow, the transgressive system tract will be characterized by lower accommodation space and might lead to more amalgamated channels. In the later stages of transgression and early highstand, the rate of formation of accommodation space decreases, therefore the potential for storage and vertical accretion also declines.

At highstand, the rate of eustatic sea-level

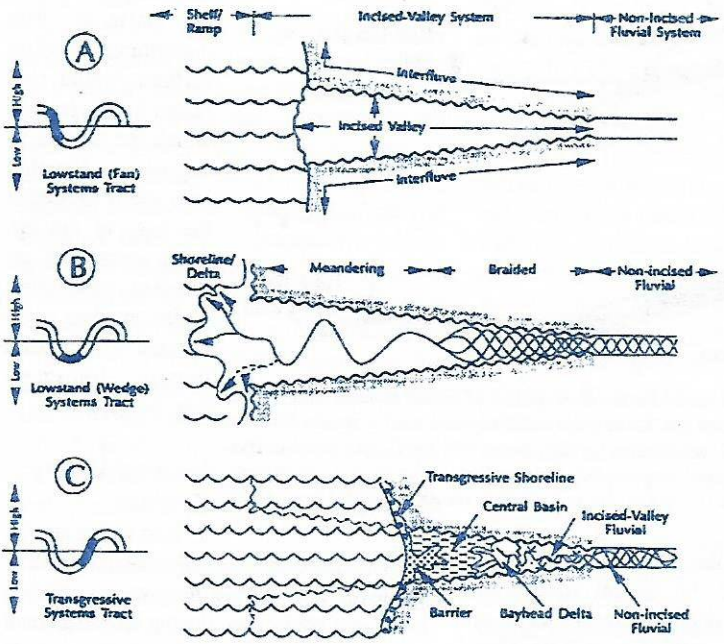


Figure 2: Schematic model for the development of incised-valley system with its nomenclatures up to the following infilling processes (from Zaitlin et. al., 1994).

rise decreases to zero and consequently the rate of addition of accommodation space slows down although continued subsidence still creates some accommodation. Lateral accretion deposits dominate the sequence with minor accumulations of fine-grained vertically accreted sediment (Wright & Marriott, 1993). If sea-level starts to fall again, different depositional systems may occur depending on the rate of relative sea-level fall and whether sea-level eventually falls below the shelf-edge.

Recognition of Stratigraphic Surfaces in Fluvial System

In area where incision of underlying marine strata has occurred, the recognition of regionally significant sequence boundaries related to changes in stratigraphic base level is comparatively straightforward. The superposition of braided river deposits on marine shales or the development of coals within marine shales allow for an unambiguous interpretation. As the thickness of continental strata increases, however, the discrimination of regionally extensive erosion surfaces, driven by allocyclic processes, from channel scours becomes much more difficult (Shanley & McCabe, 1994). Sequence boundaries reflecting an allocyclic forcing function might be identified from an understanding of those stratal geometries that signified an abrupt change in the rate at which accommodation space was created.

Interpretation of regionally extensive sequence boundaries is often made on the basis of alluvial incision. Incision due to a change in stratigraphic base level is influenced by the difference in slope between shallow marine shelves and alluvial plains. The depth of incision increases when the slope of the exposed shelf is greater than the slope of the fluvial equilibrium profile

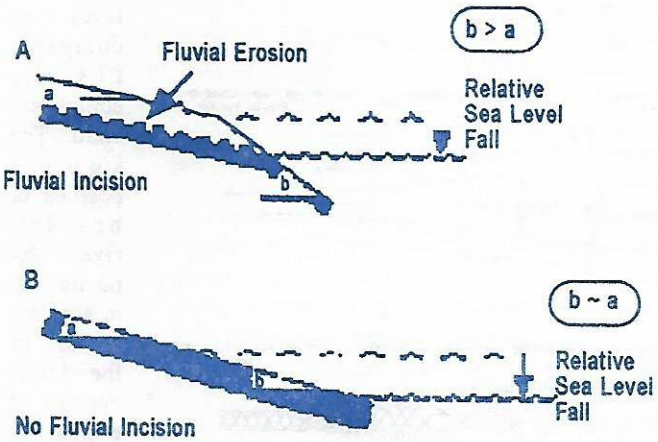


Figure 3: Schematic model for the development of fluvial incision with respect to the relative sea level fall. If the slope of the exposed shelf is greater than the slope of the fluvial equilibrium profile, there will be fluvial incision (A). Whereas If the exposed slope is the same as that of the fluvial equilibrium slope, the river does not incise (B) as it extends across the shelf (from Allen,

(Figure 3.a). If the exposed slope is the same as that of the fluvial equilibrium slope, the river does not incise as it extends across the shelf (Figure 3.b). However, most shallow marine shelves have a steeper gradient than adjacent alluvial plains and therefore a drop in relative sea level ordinarily leads to incision (Miall, 1991).

On interfluves, careful examination of paleosols is the most powerful tool for recognizing the sequence boundaries. The depth to which paleosols are developed and their maturity in part reflects the duration of subaerial exposure as well as low sedimentation rates.

Within alluvial strata, the period of maximum flooding is not represented by condensation, but rather is represented by the invasion of tidal processes into areas formerly dominated by purely fluvial processes. The maximum inland incursion of tidal processes is controlled by the interplay of fluvial drainage, rate of stratigraphic base-level rise, physiography and, to a limited extent, tidal range (Shanley & McCabe, 1994). The other practical criteria to identify maximum flooding is by analyzing the stacking patterns. The maximum flooding surfaces would represent the surface on which the regressive deposits downlap onto and is located at the base of the upward coarsening regressive succession which overlies older upward fining and thinning transgressive deposits.

Incised-Valley System

Incised valley system (IVS) created in association with a relative sea-level fall, during a lowering in base level, and back-filled during its subsequent rise, constitute one of the most common scenarios of hydrocarbon-producing reservoirs. In this context, an incised-valley system is defined as a fluvially-eroded, elongate topographic low that is typically larger than a single channel form (Figure 2.a) and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base (Zaitlin et. al. 1994). At the most general level, all valley fills can be classified as either "simple" or "compound", depending on whether they consist of a single depositional sequence or more than one sequence. Low-gradient coastal plains (i.e. coastal-plain valleys) are simple valley fills, whereas compound systems are more common in larger incised-valleys that their headwaters in a mountainous hinterland (i.e. piedmont valleys).

The criteria for the recognition of an incised-valley system below (Zaitlin et. al. 1994) represent the initial step in defining a generalized facies model:

·The valley is a negative paleotopographic feature, the base of which truncates underlying strata.

·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 a combined flooding surface and sequence boundary. The sequence boundary may be mantled by a pebble lag and/or characterized by burrows belonging to the *Glossifungites* ichnofacies (MacEachern & Pemberton, 1994). On the interfluves, the exposure surface may be characterized by a soil or rooted horizon.

*The base of the incised-valley fill exhibits an erosional juxtaposition of more proximal (landward) facies over more distal deposits.

*Depositional markers within the deposits of the incised-valley fill will onlap the valley walls.

It is critical to identify the extent of the incised-valley system in order to document the geometry of the sequence boundaries, both within and outside of the incised valley. A variety of techniques have been employed for this purposes:

*Seismic or structural mapping of the erosional surface from wireline logs.

*Mapping of third- or higher-order residual of the erosional surface in areas affected by post-depositional structure.

*Detailed isopach mapping of the valley fill or of an interval between the unconformity and an overlying horizontal marker that extends over the interfluves in order to locate anomalously thick sections confined to the paleotopographic lows.

Any simple valley fill, or each sequence in a compound fill, can be subdivided longitudinally into three segments. Segment 1 is the most seaward part of the valley, lying between the lowstand and initial highstand shorelines; Segment 2 is in the middle section and corresponds to the dimensions of the estuary at the end of the transgression; and Segment 3 is the most landward portion, lying landward of direct marine influence throughout its history. Estuarine deposits will be present in Segments 1 and 2, but are absent by definition, from Segment 3. The idealized vertical succession of facies differs between Segment 1 and 2 in relation to where the two segments lie with respect to the initial highstand shoreline (the shoreline location at the "turnaround" point between the transgressive and highstand system tracts). In Segment 1, estuarine deposits overlie lowstand and transgressive fluvial deposits and typically exhibit a transgressive stacking of facies. Estuary-mouth facies are typically partially to completely removed by wave or tidal ravinement as the shoreline backsteps, and the remaining estuarine deposits are overlain by marine sands and/or muds. In Segment 2, open marine deposits are absent because this segment lies landward of the initial highstand shoreline. In the ideal case, transgressive estuarine deposits overlie lowstand and transgressive fluvial deposits, and are themselves capped by a regressive estuarine succession that forms as the estuary fills at the beginning of the highstand. The maximum flooding surface lies near the middle of the estuarine succession and passes seaward into marine shales above the ravinement surface.

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SEDIMENTOLOGY
Volume 44, Number 5, October 1997

793 *E. F. F. Sturkell and J. Ormö.* Impact-related clastic injections in the marine Ordovician Lockne impact structure, Central Sweden
805 *S. T. Abbott.* Mid-cycle condensed shellbeds from mid-Pleistocene cyclothems, New Zealand: implications for sequence architecture
825 *V. P. Wright, S. D. Vanstone and J. D. Marshall.* Contrasting flooding histories of Mississippian carbonate platforms revealed by marine alteration effects in palaeosols
843 *A. D. George, P. E. Playford, C. McA. Powell and P. M. Tornatora.* Lithofacies and sequence development on an Upper Devonian mixed carbonate-siliciclastic fore-reef slope, Canning Basin, Western Australia
869 *A. S. Anastas, R. W. Dalrymple, N. P. James and C. S. Nelson.* Cross-stratified calcarenites from New Zealand: subaqueous dunes in a cool-water, Oligo-Miocene seaway
893 *M. Feldmann and J. A. McKenzie.* Messinian stromatolite-thrombolite associations, Santa Pola, SE Spain: an analogue for the Palaeozoic?
915 *B. Pittet and G. E. Gorin.* Distribution of sedimentary organic matter in a mixed carbonate-siliciclastic platform environment: Oxfordian of the Swiss Jura Mountains
939 *F. Massari.* High-frequency cycles within Pleistocene forced-regressive conglomerate wedges (Bradanic area, southern Italy) filling collapse scars
959 *J. E. Stout and T. M. Zobeck.* Intermittent saltation
971 Forthcoming papers

Mengenai gambar sampul:

Pada gambar ini terlihat kontak antara endapan dasar sungai dengan batu lempung dan serpih yang mengisi sungai tersebut. Pada bagian bawah dari batuan pengisi sungai ('channel fill') didapatkan banyak sisa tumbuhan yang merupakan salah satu dari yang tertua didunia (Devon) yang mudah untuk diamati. Diperkirakan endapan sungai ini merupakan bagian dari meandering channel pada bagian bawah dari 'costal plain' dan dipengaruhi oleh pasang surut (Oleh-oleh dari Herman D.). .