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Practical Aspects of Seismic Sequence Stratigraphy
(Applications to Hydrocarbon Exploration/Production)

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Abstract: Since the late 1980s, the sequence stratigraphic method has become a critical tool for hydrocarbon exploration/development projects in many frontier and mature sedimentary basins. The successful application of this method with high resolution 3D seismic data and well data is particularly important in frontier and deepwater areas, where exploration risk and capital commitment are high. Many international major and national oil companies have been using sequence stratigraphic approach as one of the main interpretation tools for the evaluation of their high impact projects. Applied correctly, this integrated interpretation method is a powerful tool that can be used to unravel the complex stratigraphy of a given basin and to dramatically increase overall understanding of various depositional models for both siliciclastic and carbonate systems.

1. INTRODUCTION

The sequence stratigraphic method involves the accurate analyses of well-log stacking patterns, terminations and configuration of seismic reflection, and high resolution of biostratigraphy (diversity and abundance of planktonic and benthonic foraminifers, and calcareous nannofossils).

The most important task in sequence stratigraphic interpretation is to establish the reliable criteria for identifying key depositional surfaces including sequence boundaries, systems tracts, and maximum flooding surfaces (see Fig. 2). Since the stratigraphic signatures result from the interaction of tectonic, eustatic, sedimentation rate, and climatic processes, the expression of depositional surfaces on conventional subsurface data (seismic and well-log) are expected to be highly variable from one basin to another. Therefore, no single model is capable of describing all the variables which control the depositional processes.
Although several renowned sequence stratigraphers who developed a number of widely used sequence stratigraphic models claimed that the key criteria illustrated on their models are easily recognizable using conventional subsurface data, this study revealed that only a few

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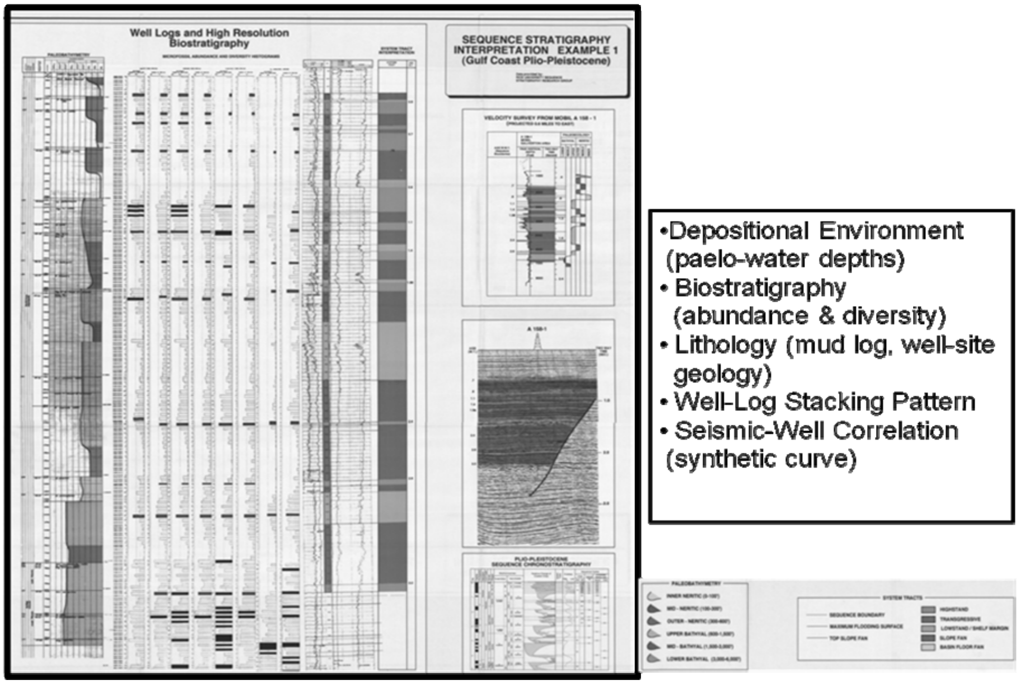
criteria can be used for identifying key depositional surfaces and genetic stratigraphic intervals. It is critical to distinguish the data driven criteria from the model driven ones. Only reliable evidences documented using mature basin examples should be used for the explanation of proposed sequence stratigraphic models. A complete sequence stratigraphic interpretation example from the offshore Gulf of Mexico basin (see Fig. 1) is particularly useful to define the fourth order cycles that develop at a time scale of less than 500,000 years (Mitchum, 1977). These fourth order cycles are known to be best developed in the Pleistocene section. The reason for the development during this time period is believed to be related to a large volume of temperate continental ice sheets. Climatic fluctuations associated with Milankovitch scale orbital cycles caused rapid changes in eustasy. Therefore, the fourth order cycles seem to have created the fully developed Plio-Pleistocene systems tracts.

In order to fully observe the lateral variations of key depositional surfaces and chrono-stratigraphically significant genetic intervals, a grid of regional 2D/3D seismic profiles and well-logs across the shelf-slop break need to be examined. Since the key sequence stratigraphic signatures are significantly differ from one depositional realm to another, a depositional profile can be subdivided into three categories: inner-mid shelf, outershelf/offlap break, and slope fan/basin floor settings.



- Depositional Environment (paelo-water depths)
- Biostratigraphy (abundance & diversity)
- Lithology (mud log, well-site geology)
- Well-Log Stacking Pattern
- Seismic-Well Correlation (synthetic curve)

Fig. 1. A complete sequence stratigraphy interpretation (H.Y. Baik, 1990)

2. INNER-MID SHELF SETTING

Landward of the shelf margin/maximum inflection point strata patterns does not develop very well because of the lack of topography in the vicinity of the sea surface. The depositional and erosional processes tend to create parallel to sub-parallel strata patterns. In this setting, it is difficult to relate depositional environments to corresponding seismic strata patterns. Therefore, the identification of key sequence stratigraphic elements rely mainly on well-log stacking patterns and seismic-well tie (high resolution synthetic seismogram and VSP data) within this depositional regime.

On seismic data, the most diagnostic feature for identifying sequence boundaries is incised valley fill. Incised valley fill is typically a parallel to subparallel onlap fill within valleys that were incised during the preceding lowstand. The most prominent incised valleys seem to be associated with type 1 sequence boundaries (see Fig. 2). These erosional surfaces are relatively well preserved and sequence boundaries can be placed at the base of the valley cuts. In some instances, interpreters could misplace sequence boundaries on seismic profile because other erosional surfaces such as revinement surfaces and overbank channels in slope fan system are commonly misinterpreted as incised valleys on the inner-mid shelf setting. Other important surfaces to identify on seismic profile are maximum flooding surface (MFS). The seismic expression of MFS is characterized by a continuous high amplitude event which is caused by impedance contrast between marine shale and nearshore sands during rapid sea-level rise. Since seismic termination patterns associated with MFS are not obvious, the positions of the MFSs should be determined on the basis of well log stacking patterns combined with biostratigraphic interpretation. Many biostratigraphic data show that the majority of the MFS and condensed sections coincide with fauna/floral abundance and diversity peaks with maximum gamma ray log curve. Although many sequence stratigraphic models (Vail, 1988) suggest that the presence of backstepping parasequences are the diagnostic evidence for identifying transgressive systems tracts and MFS, we were not able to recognize the backstepping surfaces on most of conventional seismic data we have examined due to limit of seismic resolution. It seems that the backstepping reflection pattern can be recognized only on high resolution seismic data.

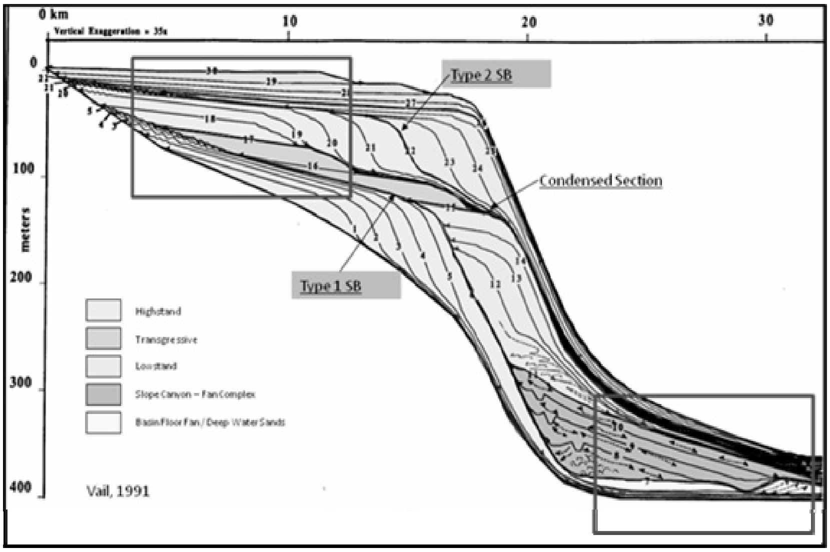


Fig. 2. Sequence stratigraphic model with strata termination patterns showing sequence boundary and associated systems tracts interpretation (Vail, 1991)

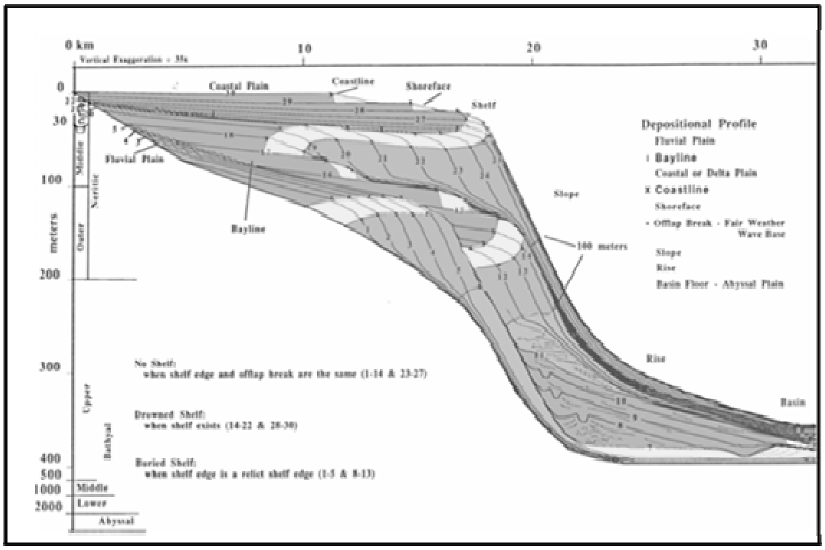


Fig. 3. Paleobathymetry and depositional profile (Bowman, 1990)

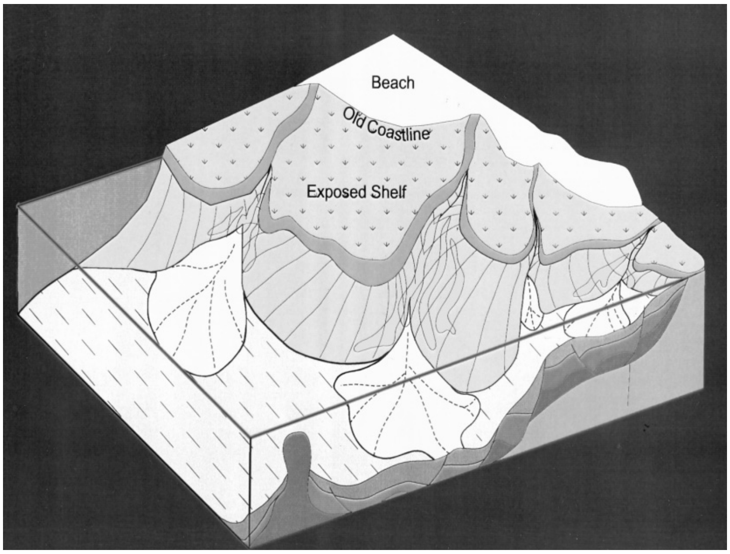


Fig. 4. Depositional model for lowstand systems tracts in deepwater depositional setting (H.Y. Baik, 1990)

3. OUTERSHELF AND SHELF MARGIN/OFFLAP BREAK SETTING

This segment of depositional profile is the ideal location to look for typical third order sequence boundaries and associated systems tracts. The typical strata patterns described in Vail's model can be identified within this depositional realm. In this depositional setting, transgressive and highstand systems tracts consist of the major components of shelf sediments since much of lowstand systems tracts are deposited beyond shelf margin/offlap break. It seems that abrupt downward shift in coastal onlap below the shelf margin commonly produces a series of obvious onlapping reflectors. Figure 2 shows that a series of the prominent onlapping reflectors which represent lowstand prograding complexes. They are readily recognizable in the vicinity of shelf margin/offlap break of the previous highstand. The offlap break often corresponds to a shoreline break clinoform near inflection point/trend. In this area, sequence boundaries (type 2 SB) are characterized by a series of parallel reflection events rarely preserve any significant termination patterns due to subtle change in baseline shift. Another controversial aspect of the sequence stratigraphic models proposed by Vail and Posamenstier is the distinction between highstand and lowstand systems tracts on conventional seismic data. Lowstand systems tracts tend to preserve aggradational offlap pattern, and highstand systems tracts are characterized by overall progradational pattern. These strata patterns have been recognized within the sequence with high accommodation space/rapid sedimentation rate. However, the distinction between the highstand and lowstand systems tracts is ambiguous on many seismic-well tie profiles. It appears that the accurate positions of these systems tracts should be determined on the basis of the well-log stacking patterns and biostratigraphic information.

4. SLOPE FAN AND BASIN FLOOR SETTING

In deepwater setting, lowstand systems tracts, including lowstand prgrading complex, slope fan, and basin floor fan, are the major components of a sequence. Highstand and transgressive systems tracts are very thin, a response to sediment starvation in this distal portion of a depositional profile. The evidences for identifying sequence elements on the shelf should not be used for the interpretation of deepwater sequences because typical deepwater sequences are condensed and seldomly preserved consistent seismic and well log patterns. We found out that seismic reflection patterns seem to be more reliable than well log stacking patterns in deepwater environments because the lithology and thickness of the lowstand systems tracts are highly variable from one sequence to another. One of the most reliable evidences to distinguish a deepwater sequence from a shallow water sequence is the presence of a series of throughgoing seismic reflectors. These events are commonly encased by thick and wavy intervals which can be interpreted as slope fan levee-channel complexes. These throughgoing reflectors represent the condensed highstand and transgressive systems tracts. In most instances, these condensed intervals coincide with the positions of the high microfossil abundance and diversity peaks. Therefore, sequence boundaries can be placed on the top of the throughgoing reflectors.

Seismic and well log expressions of a typical basin floor fan (main deepwater reservoir objective) have been a major controversial issue among sequence stratigrapher and exploration geophysicists. One of the widely used basin floor fan models published by Vail in AAPG Memoir 39 and 26 shows a series of mounds associated with major lowstands (e.g., Frigg field in North Sea). Vail suggested that mounded external configuration and internal bidirectional downlap reflectors are the main criteria for identifying a basin floor fan (see Fig. 4). However a detailed sequence stratigraphic study on the large scale basin floor fans (Marlim and Albacora fields) in the deepwater Campos basin, Brazil, concluded that the mounded feature is not necessarily one of the key evidences for recognizing a basin floor fan. The results of Petrobra's study indicate that the multiple sheet sandstone bodies situated on the basin floor setting do not show a series of mounded external configuration and a prominent bidirectional downlap pattern. The areal extent of these deepwater sand bodies were delineated accurately by 3D seismic amplitude mapping and other seismic attribute extraction such as coherency display. It seems that the shape of a basin floor fan is controlled by types of sediments, degree of compaction, intensity of contour deepwater current, and paleobathymetry. Since the development of large scale basin floor fans are closely related to major lowstand events, the accurate age determination of inter-regional unconformities on the shelf and their correlative conformities on slope and basin floor become critical for accurate sequence stratigraphic interpretation.

5. CONCLUSIONS

Detailed analysis of well-log signature, seismic strata patterns, and biostratigraphic information from a series of mature basin examples resulted in the following conclusions:
1) Applied correctly, the sequence stratigraphic interpretation method is a powerful tool that can be used to unravel the complex stratigraphy of a given basin. The successful application of sequence stratigraphic concepts is depending upon interpreter's ability to establish reliable criteria for identifying key sequence stratigraphic elements.
2) The most reliable depositional and erosional surfaces which can be correlated across a basin are tectonically enhanced first and second order sequence boundaries and peak transgression surfaces within major transgressive-regressive facies cycles.
3) The most ideal location for identifying sequence boundaries and associated systems tracts is near shelf margin/offlap break because abrupt basinward shift in coastal onlaps tend to produce a series of diagnostic strata patterns for sequence stratigraphic units near shelf-slope break.
4) Basin floor fan and shingled turbidites are main reservoir quality lowstand sands deposited in deepwater setting. Since these sand bodies lie directly on significant sequence boundaries, it is critical to determine the accurate positions and ages of sequence boundaries.

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