

## Seismic Stratigraphy: Concepts and Applications in Hydrocarbon Exploration

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**Abstract:** The objective of this article is to discuss the fundamental principles of seismic stratigraphy and its close relationship to sedimentological principles. Besides, an overview of the sequence stratigraphic analysis of seismic facies, identification of Systems Tracts, and inferring various Petroleum System elements for the purpose of Hydrocarbon exploration are also elaborated. A well-constrained seismic stratigraphic study including the definition of sequences and systems tracts as well as lithofacies information from well logs, results in the preparation of regional gross depositional environment models and facies map, predicts reservoir trends in consistency with the regional depositional setting and infers various Petroleum System elements. This approach helps mitigate exploration risk to a great extent in Sedimentary basins where very little subsurface information through drilling is available.

**Keywords:** Seismic stratigraphy, sequence stratigraphic analysis of seismic facies, Systems tract, Hydrocarbon exploration.

### Introduction

Seismic stratigraphy is the study of stratigraphy and depositional facies as interpreted from seismic data. Seismic reflection terminations and configurations are interpreted as stratification patterns and are used for recognition and correlation of depositional sequences, interpretation of depositional environment, and estimation of lithofacies. Although the underlying concept has been in practice for more than 7 decades ever since the acquisition of seismic reflection data had become routine in the Oil Industry, the term “Seismic Stratigraphy” became popular and most widely practiced after the publication of AAPG Memoir -26 “Seismic Stratigraphy: Applications to Hydrocarbon Exploration” which had compiled the seminal research work by several premier Geoscientists. The evolution of the concepts of Seismic Stratigraphy as a widely applied interpretation workflow was driven by the Oil Industry’s ever-increasing reliance on seismic data. As the Oil Industry started shifting its focus of exploration for the hydrocarbon to deeper sedimentary basins and frontier areas where well data is either sparse or unavailable, it started relying more on Seismic Reflection data interpretation which had driven much of the development of concepts, structure and application of Seismic Stratigraphy. Seismic Stratigraphy has evolved into a very important tool in the tool kit of G&G Interpreters for the Geological interpretation of seismic data to infer the depositional history of sedimentary sequences to predict the distribution of all the critical elements of the Petroleum System viz. Source, Reservoir, Trap, and Seal in Basin Scale. This paper is aimed at giving a comprehensive overview of the various concepts, mapping methodologies, and the application of Seismic Stratigraphy in Basin Scale mapping and exploration for hydrocarbons.

### Seismic Stratigraphy

Seismic Stratigraphy – as the name implies – is the study of seismic data for the purpose of extracting stratigraphic information. Seismic stratigraphy is based on the recognition of unconformity-bound sequences using stratal termination patterns of seismic reflectors and internal geometry. It is based on the principle that primary seismic reflections follow chronostratigraphic (time- stratigraphic) correlation patterns rather than time-transgressive lithostratigraphic (rock- stratigraphic) units. In other words, seismic reflectors are timelines. They cut across major lithologic boundaries, especially those defined by outcrop sections or wells. This relationship of seismic reflections to geologic timelines provides the basis for subdividing seismic reflections into packages corresponding to genetic depositional intervals. Changes in rock type produce changes in the reflectivity, which affect the wave shape seen in seismic data. Inferring stratigraphic changes and where they occur based on characteristics of seismic data is an objective of Seismic Stratigraphy. The historical use of seismic data has been in the mapping of geologic structures. Seismic stratigraphy goes beyond merely mapping structure and it aims at searching for more direct seismic evidence as to the nature of the rocks and the fluid contained within their pore spaces. It focuses on the identification of sequence boundaries in a seismic section according to specific criteria. Such sequence boundaries may coincide with horizons identified from structural interpretation. In addition, the reflection configuration in between the sequence boundaries analyzed in detail to define systems tracts, which constitute sets of similar accommodation patterns, represented by well-defined stratal patterns varying from sigmoidal to oblique, oblique to aggradational or retrogradational depositional geometries. Individual systems tracts are separated by major flooding surfaces, indicating a marked change in accommodation. A seismic stratigraphic study including the definition of sequences and systems tracts as well as lithofacies information from well logs, results in a detailed reconstruction of the paleogeography of the study area, e.g., the position of the paleo-coast. If lithofacies from well logs are not available, the large-scale

paleogeography can be inferred based on the fact, that individual systems tracts in clastic and carbonate systems are characterized by specific lithofacies associations and depositional environments.

**Basics of Seismic Stratigraphy**

**a) Depositional Sequence**

A ‘depositional sequence’ is defined as a relatively conformable succession of genetically related strata bounded by subaerial unconformities or their correlative conformities. In a depositional sequence, the scale of deposition and the controlling factors can be classified as given in Figure 1. Clastic sediments are formed by erosion of elevated grounds and following the natural relief they are deposited in basinal lows. The major part of these sediments is transported by rivers, intermittently deposited on the coast, where they are reworked by storms and currents and distributed over the shelf typically forming deltaic sediment features, prograding across the shelf and the continental slope into the basinal part. The grain size decreases with increasing distance from land. The formation thickness, its extent over the basin, and the external shape of the sediment bodies are controlled by external factors that influence accommodation space (basin subsidence, sea-level change) sediment supply in siliciclastic sediments, sediment production in carbonates, and climate.

	Scale of Deposition		Controls	
Increasing ↓	Lamina	Episodic	Storms	
	Lamina set		Floods	
	Bed		Tides	
	Bedset			
	Parasequence	Cyclic	Shifting Sediment distribution Pattern	
	Parasequence set		Sea-Level Fluctuations	
	Sequence		Long term Tectonics	

Fig. 1. Scale of deposition and their controls.

In siliciclastic depositional systems, sediment supply is essentially allochthonous and is mainly controlled by aerial extent, lithology and tectonic uplift of hinterlands and/or by climate. In carbonate depositional systems, sediment production rather takes place in-situ mostly in shelf areas and is controlled by climate and paleo-ecological factors such as water depth, nutrient supply and turbidity.

**b) Basin subsidence**

Basins are formed primarily due to ‘tectonic subsidence’ resulting from large-scale crustal movements, providing the major long-term (>3 Ma) accommodation space for the deposition of sediments. Additional accommodation space is created by the compaction of older sediments with increasing burial depths which is known as ‘compaction-induced subsidence’. ‘Thermal Subsidence’ in a basin takes place due to thermal contraction during cooling of the crust. Tectonic subsidence, compaction-induced subsidence and thermal subsidence add up as total subsidence.

**c) Eustatic sea-level change**

The eustatic sea level is the distance from the center of the earth to the sea surface. Eustatic sea level changes are global sea level changes related to changes in the volume of water in the ocean. An increase of the eustatic sea level can be generated by decreasing glaciation and increasing spreading rates of the mid-ocean ridges or more mid-oceanic ridges. Conversely, increasing glaciation, decreasing spreading rates, or fewer mid-ocean ridges lead to a fall in the eustatic sea level. Changes in the eustatic sea level led to changes in accommodation and therefore affect the deposition of sediments in marine environments. Transgression and regression define the aerial extent of the land surface which is subject to erosion and the shelfal area being available for sediment

deposition. The interaction of eustatic sea-level changes and tectonic subsidence results in changes in the amount of space available for sedimentation. Space left over from the previous eustatic cycle and space created during the current cycle is referred to as ‘Accommodation’ (Posamentier et al., 1988). Changes in accommodation lead to relative sea-level changes. Relative sea-level changes, which are exclusively controlled by eustatic sea-level and tectonic subsidence differ from changes in paleobathymetry. Paleobathymetric changes as indicated by lithofacies are controlled by changes in eustatic sea level, total subsidence, and additionally by sediment supply and production. Each sequence stratigraphic unit represents a change in accommodation rather than in eustatic sea level only.

**d) Sea-level cycles**

Sea-level low stand leads to the formation of prominent unconformities as large areas formerly below sea-level are now exposed to erosion. Sea-level highstands floods continental areas and generate a landward shift of marine sediments. A subsequent drop in sea level causes a basinward shift of the coastline, large areas fall dry again and another subaerial unconformity is formed. Such successions of sea-level change are called sea-level cycles. A cycle spans a time interval that starts with the drop in sea level, and continues during the subsequent low stand, rise of sea level, and high stand until the renewed drop of sea level finalizes the cycle. Cycles are subdivided according to their duration:

*1<sup>st</sup> order cycles:* longer than 50 million years, related to large-scale plate motions, e.g., the formation of supercontinents.

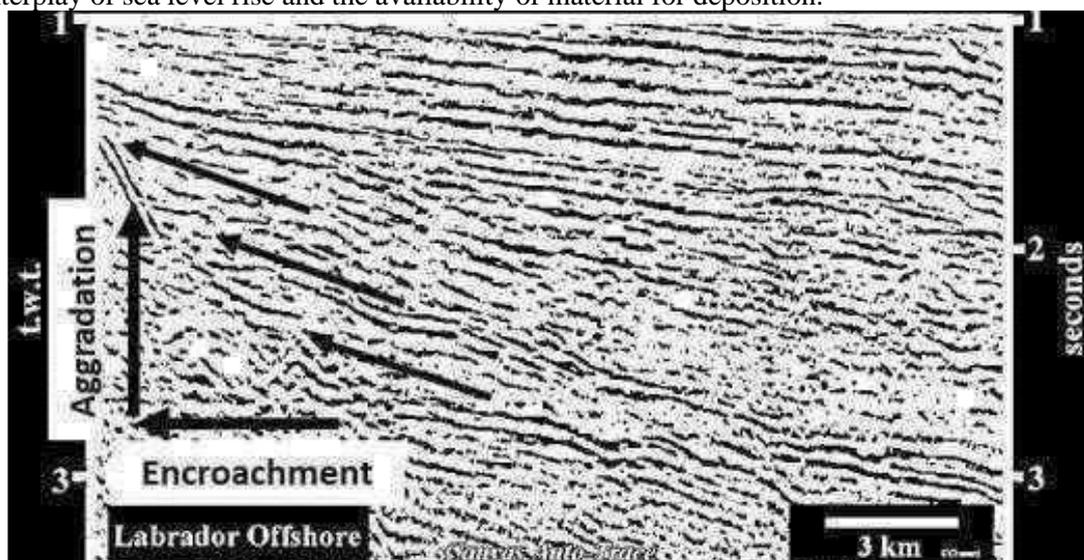
*2<sup>nd</sup> order cycles:* 3-50 Million years, governed by fluctuating volumes of the oceans due to changes in plate tectonic activity, e.g., varying spreading rates, and rates of subduction.

*3<sup>rd</sup> order cycles:* 0.5-3 Million years, related to changes "in the global ice volume, alternatively to changes of climate or lithospheric stress, termed sequences.

*4<sup>th</sup> and 5<sup>th</sup> order cycles:* Shorter than 0.5 Ma, related to cyclic perturbations of the earth's tilt and orbit. 4th order cycles last between 0.1 and 0.5 Ma and are termed ‘Parasequences’.

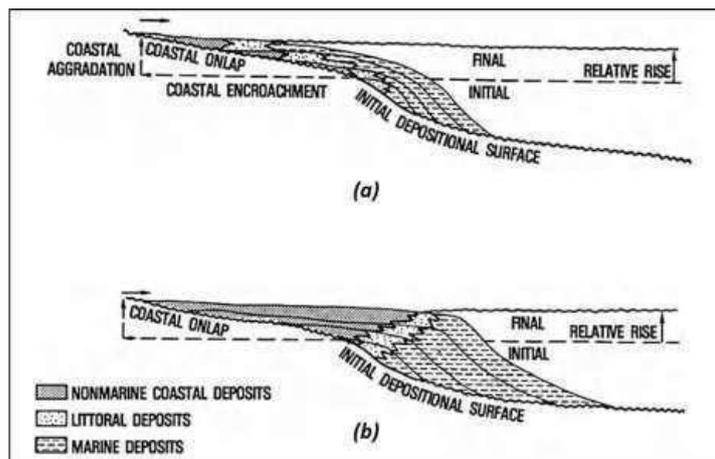
**e) Geologic Sea-level change models**

As the sea level rises compared to the land, sediments will be deposited farther and farther landward (Fig. 3.2) in a pattern called ‘coastal onlap’. The vertical distance, called coastal aggradation, is a measure of the relative rise, allowing for error because of rotation of the overall section and other factors. The associated horizontal distance is called coastal encroachment. The nature of the facies that will be deposited at any location depends on the interplay of sea level rise and the availability of material for deposition.



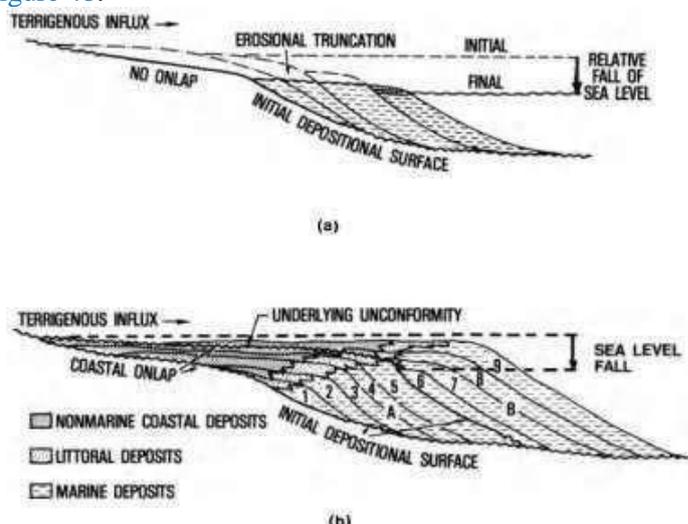
**Fig. 2.** Coastal Aggradations and Encroachment during a Coastal Onlap.

If the terrigenous influx is low, the coastline will move landward with time, producing a transgression (Fig. 3a). However, if the terrigenous influx is especially great, the coastline may move seaward with time despite the sea level rise resulting in a regression (Fig. 3b). Hence, the terms regression and transgression are not by themselves adequate to describe what happened to relative sea level.



**Fig. 3.** Patterns expected for rise in sea level: (a) if the terrigenous influx is low, a transgression results; (b) high terrigenous influx can overwhelm a sea level rise and produce a regression. (After [Vail and Thompson, 1977](#)).

In a gradual fall of sea level ([Fig. 4a](#)), successive deposition would be displaced seaward; the tops of the patterns would subsequently be eroded off as they were exposed. If a period of rising sea level should be followed by a sudden fall, we expect the entire depositional pattern to shift seaward by a considerable amount, given the pattern indicated in [Figure 4b](#).



**Fig. 4.** Patterns expected for fall in sea level: (a) a gradual sea level fall produces a gradual downward shift in depositional patterns, with the tops of the patterns subsequently eroded off and (b) a rapid fall in sea level produces a major seaward shift in the locale of coastal onlap.

**f) Key Stratal Elements**

The Seismic Stratigraphy is founded on the premise that the following key stratal elements record the history of deposition, the identification and mapping of them in Seismic reflection sections help define the depositional sequences.

1. Bounding surfaces: Unconformities & Correlative Conformities
2. Stratal terminations
3. Internal Reflection patterns
4. External Form

**Unconformities and Correlative Conformities**

Depositional sequences are bounded by subaerial unconformities at the top and bottom. A ‘Subaerial Unconformity’ is a surface formed through subaerial exposure and erosion, and includes features formed by downcutting rivers, soil processes, and karst processes. They are surfaces that form a substantial break (hiatus) in the geological record between two rock bodies. A ‘Correlative Conformity’ is a depositional surface in the basal part that correlates to a subaerial unconformity.

**Types of Unconformities:**

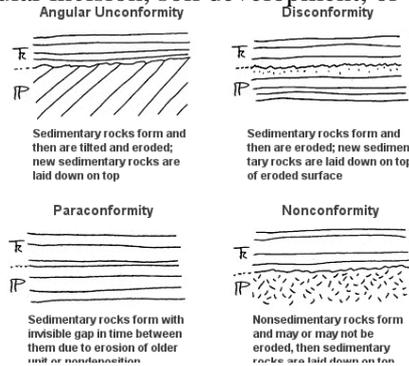
There are four types of Unconformities recognizable in the rock record (Fig. 5).

*Angular unconformity*

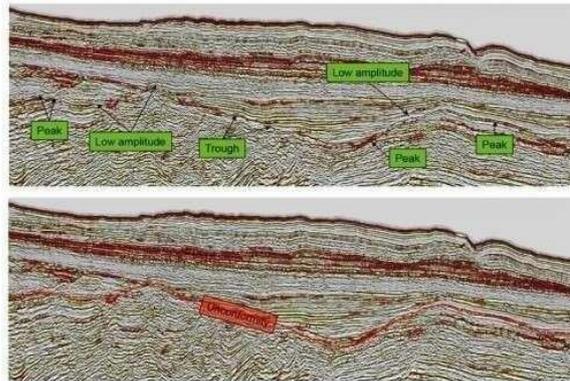
An angular unconformity is an unconformity in which horizontally parallel strata of sedimentary rock are deposited on tilted and eroded layers, resulting in angular discordance with the horizontal layers above. Further orogenic activity can deform and tilt the entire sequence later.

*Disconformity*

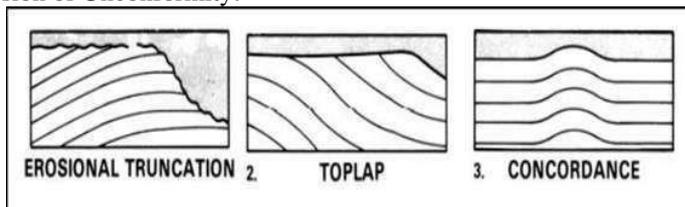
Disconformities are unconformities in which beds above and below are parallel but a well-developed erosional surface can be recognized, by irregular incision, soil development, or basal gravel deposits on top.



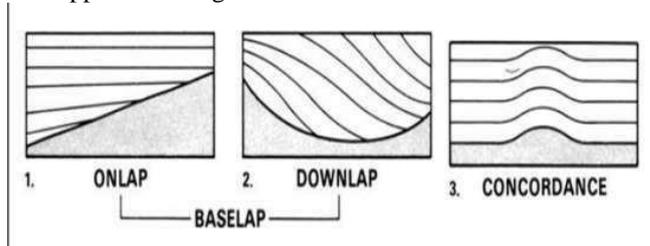
**Fig. 5.** Types of Unconformities. Symbols on the left are for Pennsylvanian age (bottom) and Triassic age (top), separated by at least 50 million years. Source: Andrew Alden (2011).



**Fig. 6.** Seismic expression of Unconformity.



**Fig. 7.** Relationship with the upper bounding surface.



**Fig. 8.** Relationship with the lower bounding surface.

*Paraconformity*

A paraconformity is a type of disconformity where separation is a simple bedding plane with no apparent buried erosional surface in this type of unconformity strata above and below are parallel; no apparent erosion occurs

and the surface of the unconformity resembles a simple bedding plane. It is also called pseudo-conformity or non-depositional unconformity. Short Para conformities are also known as diastems.

*Nonconformity*

A nonconformity exists between sedimentary rocks and metamorphic or igneous rocks when the sedimentary rock lies above and was deposited on the pre-existing and eroded metamorphic or igneous rock. In a seismic section, a regional unconformity can be identified by usually a discontinuous reflector with contrasting reflection pattern above and below (Fig. 6)

**Stratal terminations**

Stratal terminations describe geometric relationships between a strata/reflection and the surface against which it terminates. Stratal terminations are categorized into top-bounding relationships and bottom-bounding relationships. The bounding configurations of reflections at the top of seismic sequence units are base erosional truncation, toplap, and parallelism to the boundary - Concordance (Fig. 7). The bounding configurations of reflections at the base of seismic sequence units are base onlap, downlap, or parallelism to the boundary - Concordance (Fig. 8).

**Upper Boundary Relationship**

*Erosional truncation:* It defines an unconformity due to heavy erosion, and sediment bypassing due to rapid sea-level fall (Fig. 9). Erosional truncation, implies that the sedimentary unit formerly extended significantly beyond its present possibly being exposed above the water and that the top of the unit was removed.

*Toplap:* Lapout represents a hiatus due to non-deposition (Fig. 9). Toplap implies deposition near the wave base where there was appreciable energy during or shortly after the deposition of the sediments so that there is a reasonable probability that sorting of grain sizes by the wave energy will have occurred.

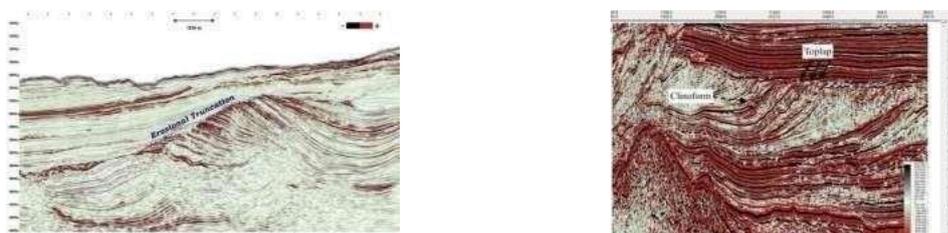


Fig. 9. Erosional truncation & Toplap

**Lower Boundary Relationship**

*Onlap:* An initially horizontal stratum laps out against an initially inclined surface, or an initially inclined stratum laps out up dip against a surface of greater initial inclination (Fig. 10).

*Downlap:* A downlap is a discordant geometric configuration, in which initially inclined strata terminate downdip against an initially horizontal or inclined surface (Fig. 10).

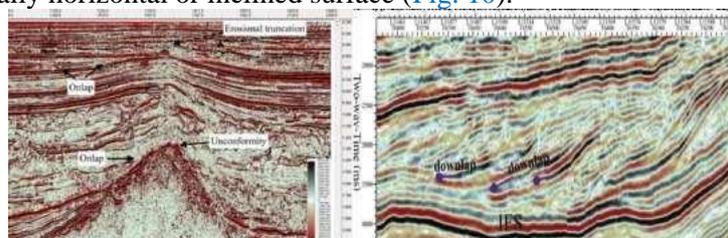


Fig. 10. Onlap and Downlap.

The distinction between onlap and downlap is based on the geometry, that is, whether the onlapping bed at its termination is flat to dipping upward (onlap) or dipping downward (downlap). Sometimes onlap relates to those portions of the sequence nearest the coast and downlap to those portions at the seaward end of the unit. In the case of onlap, the distinction implies thinning because there was not much room for deposition. In the case of

downlap it implies thinning because there was not much sediment available. In the early phases of an interpretation, distinction should be made on the basis of geometry only, without regard for the implied reason. Often no distinction is made; then both onlap and downlap are called base lap. In a completely developed sequence, the top and bottom boundary relationships are seismically well-defined and their stacking pattern help to subdivide the sequence into its component system tracts (Fig. 11).

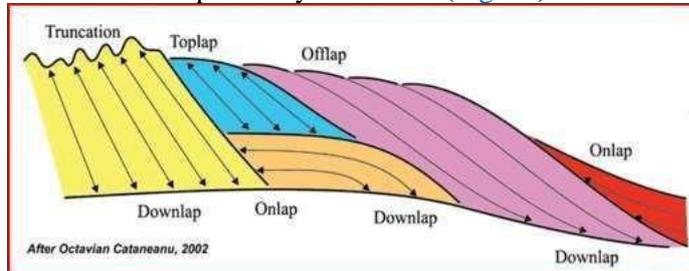


Fig. 11. Schematic diagram of a complete sequence showing various top and Bottom boundary relationships.

*Internal Reflection patterns:* Analysis of internal reflection geometry constitutes an important part of Seismic facies analysis. The stratal reflection patterns exhibited by sequences are classified into a) stratified and b) unstratified reflections.

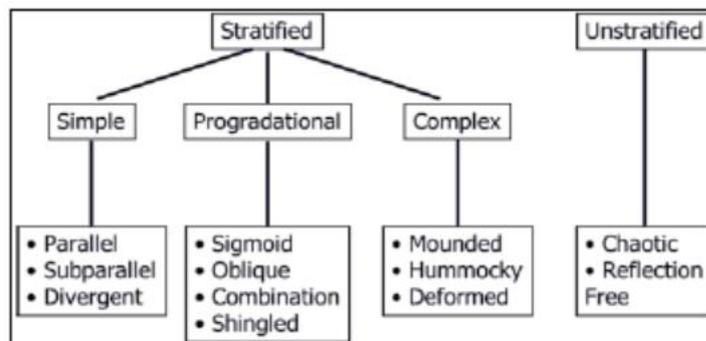


Fig. 12. Classification of Stratal reflection Patterns.

**Stratified: Simple Reflection Configurations**

The most common types of reflection configurations consist of parallel, subparallel, or divergent reflections.

*Parallel:* Parallel reflection configuration in general represents a very calm depositional environment with slow subsidence and stable sediment supply over long period (Fig. 13). The low depositional energy results in layered rocks without much tectonic disturbance. These type of reflect in configurations are seen in stable shelves as wells as in the basinal settings where the depositional dip is horizontal to very gentle.

*Subparallel:* Sub parallel reflection patterns in general occur in areas of oscillating energy conditions with relatively stable subsidence history (Fig. 14). They denote relatively higher energy regimes as compared to the parallel reflection pattern.

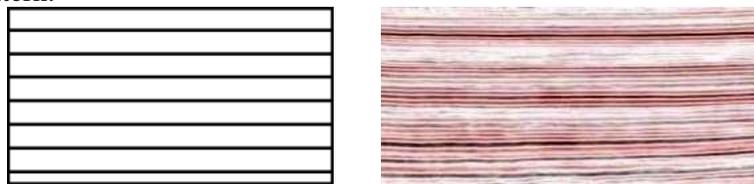
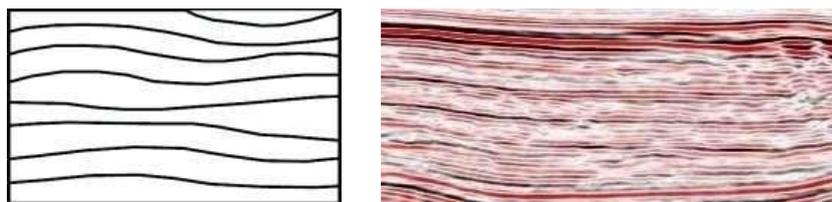
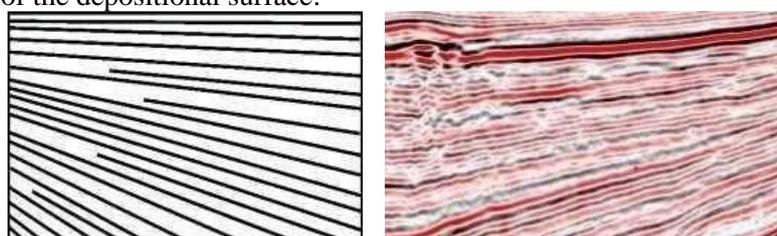


Fig. 13. Simple parallel reflection pattern.



**Fig. 14.** Simple sub parallel reflection pattern

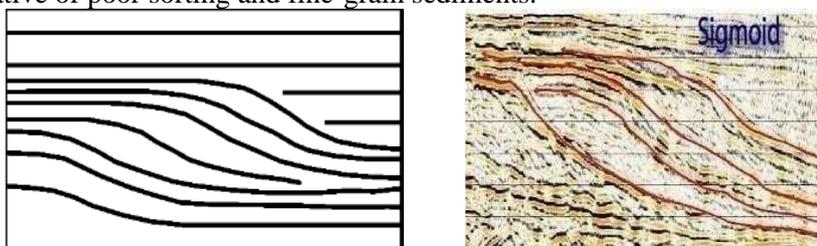
*Divergent:* Divergent reflections gradually spread out, almost always in the down-dip direction, indicating gradual basin subsidence during deposition, with gradual basin ward tilting (Fig. 15). New reflections appear between other reflections as units thicken and become resolvable. Divergent reflection configuration is characterized by a wedge-shaped unit in which most of the lateral thickening is accomplished by thickening of individual reflection cycles within the unit, rather than by onlap, toplap or erosion at the base or at the top of the stratigraphic cycle. Divergent configurations suggest lateral variations in the rate of deposition, or progressive tilting of the depositional surface.



**Fig. 15.** Simple divergent reflection pattern

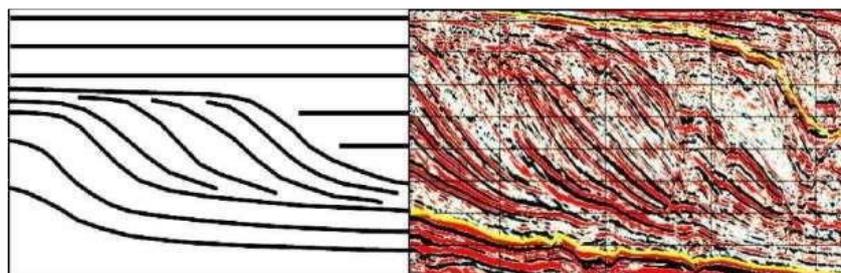
**Stratified: Progradational**

*Sigmoidal Progradational:* The sigmoid pattern is distinguished by a very gentle "s" shape, with the top of the pattern tending to parallel the sequence boundary (Fig. 16). It represents deposition in quiet (usually deep) water with low depositional energy so that the top of the unit was not disturbed during deposition; the sigmoid pattern therefore is indicative of poor sorting and fine-grain sediments.



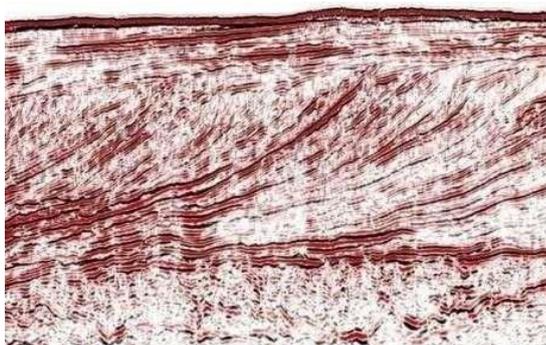
**Fig. 16.** Sigmoidal progradation reflection pattern.

*Oblique Progradation:* The oblique pattern shows toplap or angularity with the upper boundary of the sequence (Fig. 17). It represents deposition near the wave base in a high-energy environment, and thus sorting of grain sizes may have occurred at the tops of oblique patterns. whether oblique patterns contain fairly clean sands depends also on whether sand-size grains were available for deposition. The distinction between oblique toplap and erosional truncation may also be difficult to make, but this distinction is less important because both probably involve enough energy to have provided sorting.



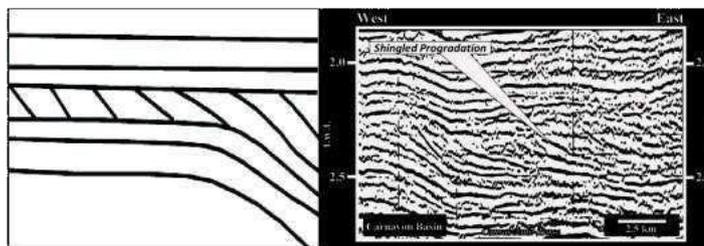
**Fig. 17.** Oblique progradation reflection pattern.

*Combination of sigmoidal and Oblique Progradation:* Complex sigmoid-oblique progradational patterns are prograding clinofolds patterns of a combination of variably alternating sigmoid and oblique progradational reflection configurations within a single seismic interval (Fig. 18). In this tentative interpretation, the upper segments (topsets) are characterized by complex alternations of horizontal sigmoid topset reflections and segments of oblique configuration with toplap terminations. This variability implies strata with a history of alternating upbuilding and depositional bypass in the topset segment, within a high- energy depositional regime. This reflection configuration illustrates short segments of toplap within a seismic sequence rather than at its upper boundary. The short segments of toplap indicate a number of smaller scale depositional intervals whose boundaries are below seismic resolution except where toplap is prominent. The smaller scale units are commonly interpreted as discrete lobes of a prograding unit.



**Fig. 18.** Combination of Sigmoidal and Oblique progradation reflection pattern.

*Shingled Progradation:* A shingled progradational reflection configuration is a thin prograding seismic pattern, commonly with parallel upper and lower boundaries, and with gently dipping parallel oblique internal reflectors that terminate by apparent toplap and downlap. The overall pattern resembles that of the parallel oblique progradational configuration, except that the thickness of the interval is just at the point of seismic resolution of the oblique beds. Shingled seismic configurations are most common in seismic intervals interpreted as shallow water or deep water prograding depositional systems.



**Fig. 19.** Shingled progradation reflection pattern.

**Stratified: Complex Mounded**

Mounded reflection configurations (Fig. 20) are interpreted as strata forming elevations or prominences rising above the regional level of the surrounding strata. Most mounds are topographic build-ups resulting from either clastic, volcanic depositional processes, or organic growth of carbonate sequences such as reefoidal bodies. Compaction of these bodies, mounded geometries, and particularly onlap mounded reflection configurations can be post- depositional, created due to differential compaction of the sediments. The sandy facies filling the

channel morphology are less compactable than its surrounding shale sediments. Differential compaction is used to predict if a channel is filled by sandstones which result in onlap mound or clays where absence of onlap mound formation.

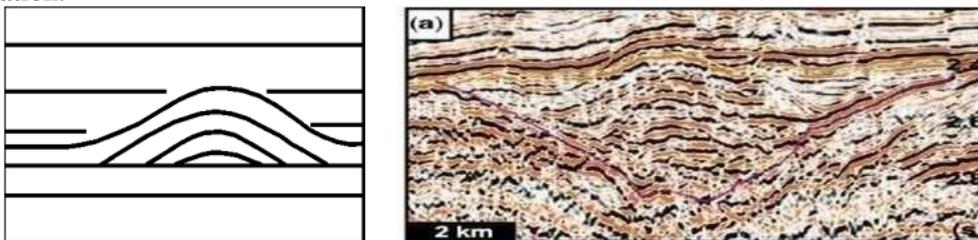


Fig. 20. Mounded reflection pattern.

**Hummocky**

A hummocky clinofolds reflection configuration (Fig. 21) consists of irregular discontinuous subparallel reflection segments forming a practically random hummocky pattern marked by non- systematic reflection terminations and splits. Relief on hummocks is low as the limits of seismic resolution are approached.

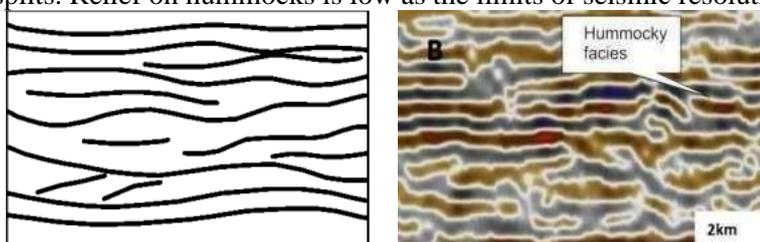


Fig. 21. Hummocky reflection pattern.

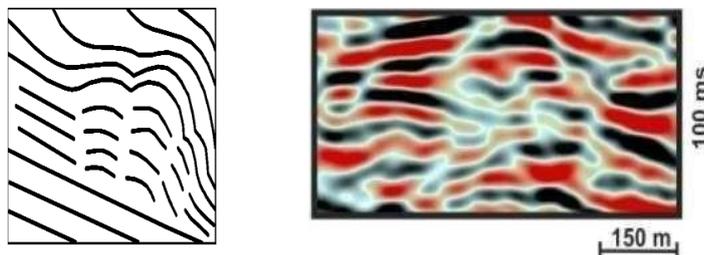


Fig. 22. Deformed reflection pattern

**Deformed**

Deformed reflection pattern (Fig. 22) as opposed to mounded reflection comprise of contorted to chaotic reflection pattern which are discontinuous. They are interpreted to be formed due to synsedimentary contemporaneous deformation.

**External Form**

There are four external forms that can be generally recognized in Seismic sections. They are: 1) Channel Fill, 2) Trough Fill, 3) Basin Fill and 4) Front Slope Fill.

**Channel Fill**

Channel fill pattern is the most common and easily recognizable external form. It can occur in Fluvial, Shallow marine as well as deep water environments and need to be distinguished based on the overall depositional setting and plan form geometry. A typical channel fill with internal bimodal fill pattern is given in Figure 23.

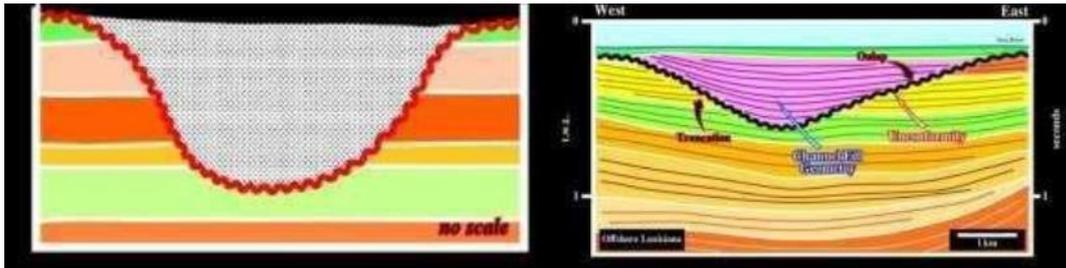


Fig. 23. Typical Channel Fill with internal bimodal onlaps.

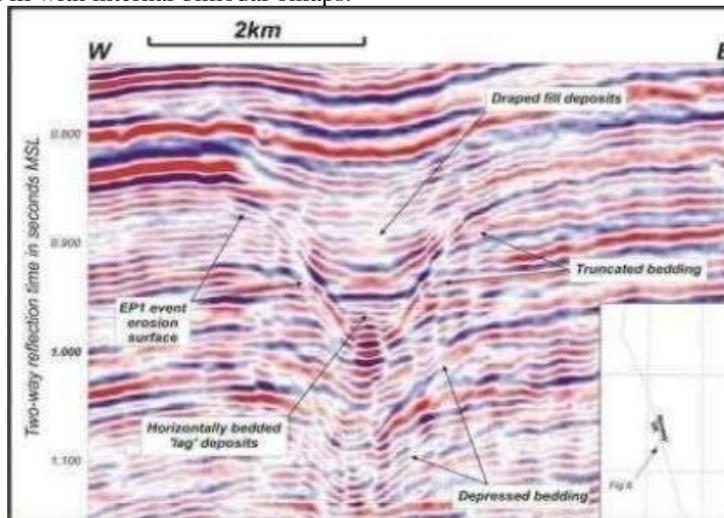


Fig. 24. Seismic section showing a Channel with typical internal fill characteristics.

A 3D seismic section depicting a deep channel incision is given in Figure 24. It illustrates various components like

- a) basal erosion surface,
- b) truncated bedding,
- c) horizontally bedded ‘lag’ deposits and
- d) draped fill deposits.

### Trough Fill

An external geometry pattern is called trough fill when the depositional anomaly is structural that is when the depositional surface is not created by local or regional erosion but by folding of preexisting strata.

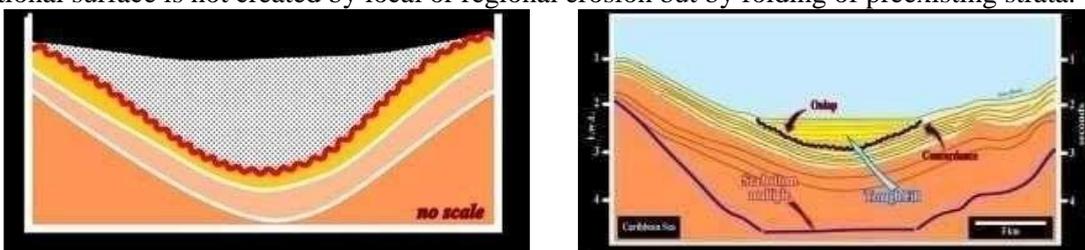
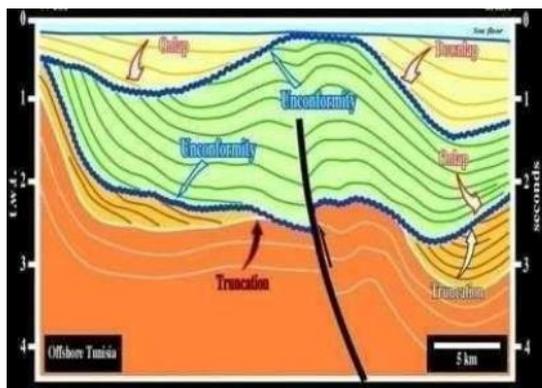


Fig. 25. A Trough Fill with typical internal fill characteristics.

The internal fill configuration of trough fills can vary considerably. Also, the fill may show more lithological heterogeneity (Fig. 25).

### Basin Fill

Deposition that occurs on a basinal scale due to regional tectonic forces are classified under Basin Fill.



**Fig. 26.** A Basin Fill with typical internal fill characteristics.

The above figure (Fig. 25) depicts the line drawing of Basin Fill. The green sequence represent the Basin Fill sequences. The lower unconformity at the base of the green interval, corresponds to an external basin fill. The underlying reflection terminations of the lower unconformity, are truncations and the overlying terminations correspond to tilted or deformed onlap. The frontal slope fill pattern in the above figure (Fig. 27) is composed of a typical progradational internal fill configuration. The green seismic interval underlying the front fill depositional surface, corresponds to a front slope fill base. The shelf break is on the eastern part of the line. There is no significant erosion associated with this front slope fill.

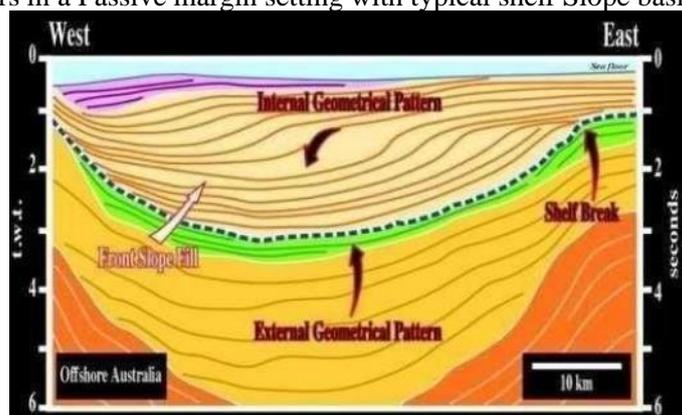
### Seismic stratigraphy interpretation procedure

The seismic stratigraphy interpretation procedure consists of the following steps.

1. Seismic sequence analysis
2. Well-log sequence analysis
3. Synthetic, well-to-seismic tie
4. Seismic facies analysis
5. Interpretation of depositional environment and lithofacies
6. Sequence stratigraphic modelling
7. Application to Hydrocarbon Exploration

### Frontal Slope Fill

A Frontal Slope Fill occurs in a Passive margin setting with typical shelf Slope basin configuration.



**Fig. 27.** Frontal Slope Fill with typical internal fill characteristics.

### 1. Seismic sequence analysis

It defines the genetic reflection packages referred to as seismic sequences and seismic systems tracts by identifying discontinuities on the basis of reflection termination patterns.

Two patterns, onlap and downlap, occur above the discontinuity and three patterns, truncation, toplap, and apparent truncation, occur below the discontinuity.

Sequence boundaries are characterized by regional onlap and truncation. With one exception, systems tract boundaries within a sequence are characterized by regional downlap.

### 2. Well log sequence analysis

In this step we make preliminary estimates of sequences and systems tracts by first interpreting the depositional lithofacies on wireline logs using cores and cuttings to calibrate the log. Following this, we estimate sequences and systems tracts from the interpreted lithofacies, and determine changes in accommodation from parasequence stacking patterns. We check the preliminary estimates of sequences and systems tracts in two ways: by correlation between wells with biostratigraphy-time correlations, well- log marker-bed correlations, and correlation with the global cycle chart; and by correlation with seismic profiles.

### 3. Synthetic Well to Seismic tie

Its purpose is to tie, as carefully as possible, information from well logs to the seismic section. There are two primary objectives. The first is to tie the well-log depth information to seismic time. The second is to know what causes the seismic reflection by understanding the constructive and destructive interference patterns of the individual wavelets that originate from the impedance contrasts. After the synthetic ties are completed, the sequence and systems tract boundaries can be adjusted to the best solution.

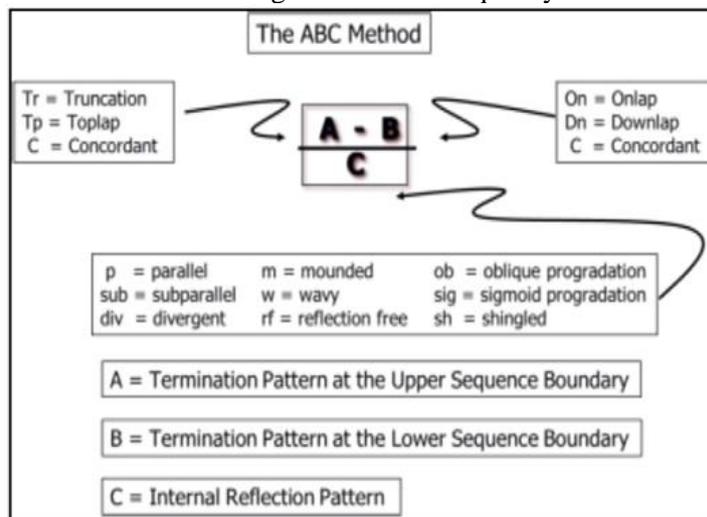
### 4. Seismic Facies analysis

Seismic facies analysis involves qualitative to quantitative analysis of seismic character to infer areal trends in either lithology, paleoenvironment, or both (e.g., outer shelf shales). Generally, seismic character is analyzed from two standpoints: external form (geometry) and internal character. Internal form includes the continuity, frequency, and amplitude of seismic reflections (Table 1).

**Table 1.** Seismic reflection characteristics of seismically definable sand bodies.

Feature	Significance
Amplitude	-Impedance Contrast (Significant stratal surfaces) - Bed spacing /tuning - Lithofacies - Fluid contact
Continuity	- Lateral stratal continuity - Depositional processes
Frequency	- Bed thickness - Fluid content
Geometry	- Depositional

Many of these parameters relate to lithology or the processes responsible for deposition and thus are often used to interpret sand body origin and reservoir type. Others relate to the acoustic impedance contrast, tuning, etc., and thus seismic resolution plays a role in their discernible patterns of occurrence. Bed or stratal continuity is assumed to exceed the Fresnel zone width for a given seismic frequency.



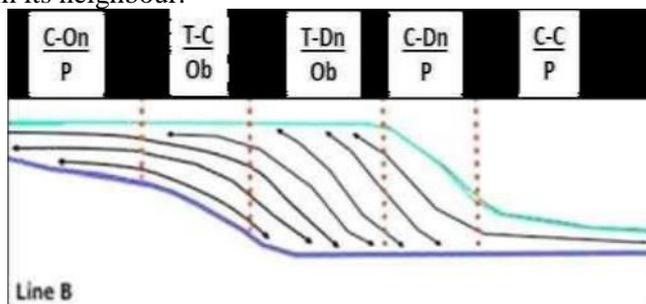
**Fig. 28.** Ramsayer’s A-B-C Seismic facies mapping.  
**External Form and Internal Geometry-A-B-C Mapping**

Seismic facies mapping was definitively explained by Ramsayer (1979), based upon 2D seismic sections interpreted prior to the advent of seismic workstations. This is referred to as the “A-B-C” mapping approach, as observations are made upon the upper boundary (A), the lower boundary (B), and internal reflection character (C) (Fig. 23). The codes used to mark the top, bottom and internal pattern are given in the following Table 2.

**Table 2.** Seismic facies mapping codes (modified from Ramsayer,1979).

Description	Position	Code	Explanation	Comments
Top	A	C	Concordant	Often Associated with Parallel internal reflections
		Top	Toplap	Non erosional
		Down	Downlap	Different from double downlap as in Mounding
		Di	Divergent	
		Tr	Truncation	Associated with erosional unconformities
Base	B	C	Concordant	
		Top	Toplap	
		Down	Downlap	
		Di	Divergent	
		Tr	Truncation	
Internal	C	P	Parallel	
		Ob	Oblique	
		Si	Sigmoidal	
		Mo	Mounded	
		SubP	Subparallel	
		Sh	Shingled	
		W	Wavy	
		Rf	Reflection Free	

For example, a prograding seismic package with oblique clinoforms, toplap at its upper surface and downlap at its base would be noted as Top-Dn/Ob (Fig. 24). In this example each line is subdivided into seismic facies units where each unit differs from its neighbour.



**Fig. 29.** A-B-C Seismic facies mapping example.

After the individual seismic lines are interpreted in terms of facies distribution, the inferred zones are marked on a map in terms of the stratal geometry (Fig. 25). Zones such as wedge outs, progradation and sheet are mapped from different seismic lines and the patterns brought out clearly on the map. A reasonably close grid 2D data set would suffice to bring out the initial facies’ distribution on a regional scale.

**5. Interpretation of depositional environment and lithofacies**

This analysis is aided by the objectively determined seismic facies parameters coupled with a maximum knowledge of the regional geology. The deposition of clastic sediments mainly transported by rivers into the ocean is, in particular, controlled by the velocity of currents and by water depth. Coarse-grained sediments will only be transported if the velocity is high enough (above a sediment specific velocity threshold); they will be deposited on the sea floor if the velocity diminishes below this threshold. Fine-grained sediments like clay particles remain in suspension at a much lower velocity and thus can be transported much farther than the coarse-grained material. With increasing bathymetry, the turbulence generated at the sea floor by wave action and

currents decreases rapidly from Coastline to basin floor. Consequently, the grain sizes also will decrease basin wards and with increasing distance from the mainland. This depositional mechanism generates a zonal distribution of clastic marine sediments at the basin margin ("sedimentary facies belts"). Thus, it is possible to predict the lithologic distribution within a sediment wedge which prograde across the margin into a basin: sands will dominate the upper near- coastal region (proximal), while clay will be deposited in the basinal parts (distal). During a sea-level rise, these belts will migrate landwards, during a sea-level fall they will migrate basin wards. The lateral sediment distribution within these belts may change considerably with each sea-level fall or rise.

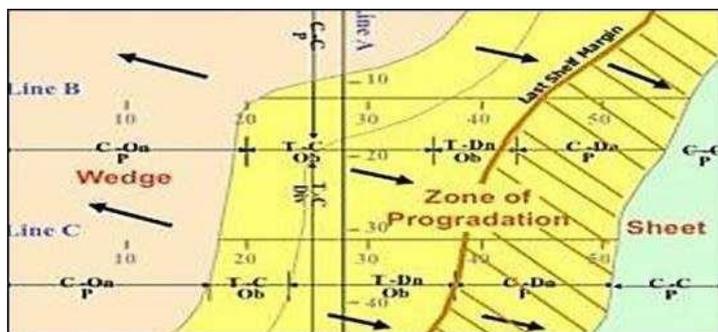


Fig. 30. A-B-C Seismic facies classification of zones.

In the above example, based on the synthesis of other available geological data, the broad depositional environments are inferred. The wedge area corresponds to the landward side fluvial / non marine environment and the zone of progradation is divided into Transitional/ marginal marine (T-Dn/Ob) to slope setting (C-Dn /P). Finally, towards the basinward side, where low energy (C- C/P) seismic facies are mapped, it is interpreted to be the basinal environment. In this case, we could decipher a basin extending from West to east with the shelf, slope and basinal configuration brought out clearly. Thus, systematic seismic facies mapping has helped to interpret regional depositional environments with high degree of consistency.



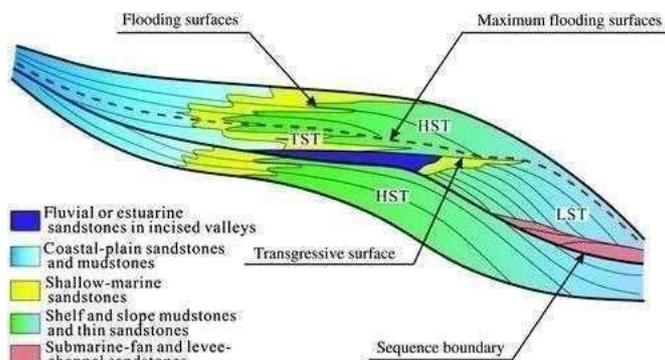
Fig. 31. A-B-C Seismic facies interpretation of depositional patterns, see 6).

### Sequence Stratigraphic modelling

In a seismic section, changes of sea-level are indicated by groups of differing reflection patterns. Three subunits can be differentiated within a single seismic sequence, depending on the varying duration of the individual segments of a sea-level cycle. Their recognition in seismic data depends on their thickness and the seismic resolution. These subunits are called "systems tracts" (Fig. 27). They represent a set of depositional systems related to an individual sea-level lowstand, rise or highstand. Systems tracts within a depositional sequence are bounded by physical discontinuities, which represent major marine flooding. The oldest and therefore, basal systems tract of depositional sequence is the Lowstand Systems Tract (LST). It consists of sediments deposited during late sea-level fall to stillstand. The ratio between the rate of eustatic fall and the rate at the shelf edge is, however, different. Lowstand systems tracts are equally overlain by the Transgressive System Tract (TST) which is deposited during rising sea-level and finally by the Highstand Systems Tract (HST) deposited during late sea-level rise, stillstand and early sea- level fall. Lowstand and transgressive systems tracts are separated by the transgressive surface. The maximum flooding surface, which is indicated by downlap reflection terminations in seismic sections, separates transgressive and highstand systems tracts.

### Lowstand Systems Tract (LST)

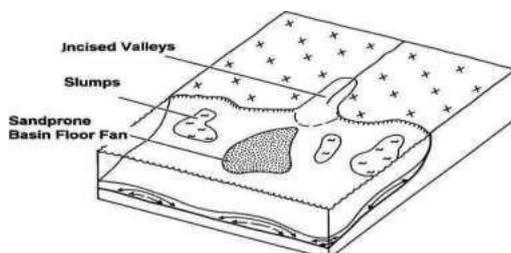
The LST represents the lowermost and oldest unit of a depositional sequence directly overlying the subaerial unconformity at the base of the depositional surface in shelfal areas. The LST consists in general of alluvial and estuarine coarse-grained clastics with little floral and faunal content. Within the LST of a shelf setting the following sediment wedges may be distinguished: Basin Floor Fan (BFF), Slope Fan (SF) and Low Stand Wedge (LSW).



**Fig. 32.** Three Tract Sequence Stratigraphy model.

*Basin floor fan (BFF)*

Lowstand basin floor fans are associated with the time of rapid eustatic fall, when sea level falls below the shelf break and sediments are transported across the shelf in incised valleys and rapidly dumped into the basin. Lowstand fan sand lobes may develop as relatively isolated lobes or as huge basin wide accumulations (Fig. 28). During a Sea level fall, the paleo-shelf exposed to slow erosion will be dissected by river valleys. These valleys extend into shelf margin and may continue basin wards as deeply incised submarine canyons. Sediments which are transported by rivers across the shelf are commonly coarse clastic erosional products (sand, silt) and form delta-like features known as fans at the canyon mouth. Perpendicular to their strike these features resemble elongate mounds. The top of these mounds is an unconformity surface marked by the downlap terminations of the reflections above.



**Fig. 33.** Basin Floor Fan.

*Slope fan (SF)*

Slope fan develops during a period of major headward erosion and bank collapse of the submarine canyons. Basin subsidence begins to create a very slow rise in the position of the sea level relative to the basin margin, as the rate of eustatic sea level fall slows and approaches zero at the lowest part of the eustatic cycle (Fig. 29). Slope fan sediments also form delta-like features. In contrast to the basin floor fans described above, slope fans are distributed over a large area over the slope. They might locally overlie the basin floor fans. These deposits are frequently formed by turbidity currents or debris flows and transported through meandering channels. They might be deposited as turbidites on both sides of the channels (leveed channel deposits). In any case, slope fan sediments are finer grained than basin floor fan sediments.

*Lowstand Wedge (LSW)*

The lowstand wedge represents the most important and frequently the thickest developed element of the lowstand systems tract (Fig. 30) it is formed by sediments prograding basin wards due to rising relative sea-level. The combined effect of slow eustatic sea level rise and continued basin subsidence shifts relative position of the sea level upward toward the old shelf-slope break. Rivers deposit shelf sediments beyond the old shelf break and bay, delta and shore face sands begin to accumulate on the upper topographic slope. These units prograde laterally into the basin, resulting in deposits in bathyal to abyssal water depths composed predominantly of shales with few thin turbidite sands. The lithology distribution in this wedge is much more

differentiated than in the above- described features and it consists of thick shaly deposits in its distal part. The rising sea- level gradually floods the paleo-shelf and consequently the river channels are filled with sediment. The channel- fills often consist of coarse clastic sediments and represent excellent HC reservoir rocks.

**Transgressive Systems Tract (TST)**

The transgressive systems tract is deposited during eustatic sea-level rise after the lowstand (Fig. 31). The coast line is shifted landwards and the shallow shelf is flooded. As the bathymetry increases, large areas are gained landward to accommodate sediments resulting in widespread deposition in the inundated shelf. Also, the sediment input is in general reduced due to reduction in the provenance area. Consequently, the TST is only a thin sediment wedge compared to the underlying LST. The boundary between LST and TST is the ‘transgressive surface’ characterized, in general, by extremely shallow downlap reflection terminations. In the seismic section it is clearly marked by the retrogradational pattern of the down laps in the basin and by a landward shift of the onlap positions of the parasequences often called ‘back stepping’ pattern. TST is not developed in the lower part of the basin except for a condensed section consisting of pelagic to hemipelagic marine sediments with a low content of terrigenous material. The top of the TST is marked by the ‘maximum flooding surface’, representing a downlap surface of prograding reflectors belonging to the overlying highstand systems tract. It marks the change from the TST to the highstand systems tract (HST) and indicates the furthest landward position of the coastline and the highest positive rate of accommodation change.

**Highstand systems tract (HST)**

The highstand systems tract represents the youngest member of the depositional sequence. It is developed during the late sea-level rise, stillstand and early fall (Fig. 32). During the early HST coastal onlap migrates landward, parasequences aggrade- build vertically. With sea-level stillstand and initial fall (late highstand), coastal onlap reverses, accompanied by strong progradation. Basinward dipping reflections of prograding clinofolds characteristically downlap on the top of the underlying maximum flooding surface. Because of the subsequent fall of sea-level, the HST is bounded by an unconformity at its top. This unconformity also marks the top of the depositional sequence. Coarse- grained sediments dominate the near coastal areas of the highstand systems tract. Depending on the distance from the sediment source the shelf itself, is dominated by sediment by- pass and minor erosion. Thus, the shelf can be recognized by characteristic toplap terminations on the seismic section, caused by strong progradation or erosion during the subsequent LST. In basins with shelf-break margins, slope deposits are dominated by slumps, slides and turbidity currents. In the seismic section they are marked by chaotic reflection patterns

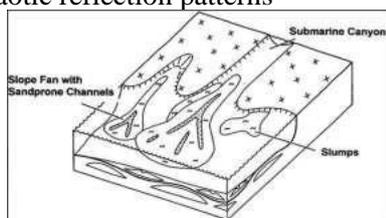


Fig. 34. Slope Fan

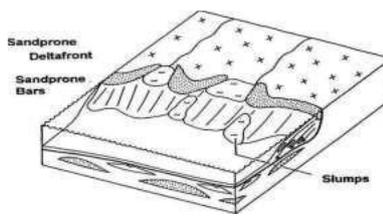


Fig. 35. Lowstand Wedge

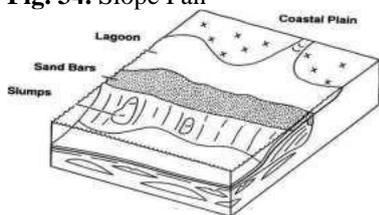


Fig. 36. Transgressive Systems Tract

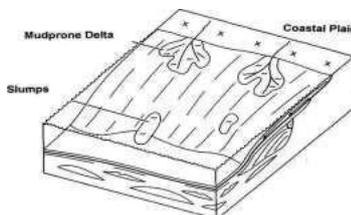


Fig. 37. Highstand systems tract

**Application to Petroleum Exploration and Exploitation**

The major reason for developing seismic stratigraphic maps is to reduce critical risk in exploration and to extract benefit from hydrocarbon discoveries. Sequences and Sequence sets are large scale elements primarily used for global, regional, and local exploration. Field and compartment scale elements are found in parasequences, parasequence sets, and high frequency sequences but these are not normally resolvable on conventional seismic data. Systems tracts are the link between these two scales but are often under-utilized. The application of seismic

stratigraphy in devising reliable work flows to predict the presence of various Petroleum System elements through detailed systems tract mapping and analysis is discussed in this section.

### **Lowstand Systems Tract (LST)**

The lowstand systems tract (LST) and lowstand sequence are the most economically important elements of any sequence (Posamentier et al., 1992). Much attention has been devoted to LSTs as the greatest remaining potential in many plays lies in deeper and depositional downdip areas where LST/LSSs are more common than HST/HSS's and TST/TSS's (Sneddon et al., 2002). The potential for stratigraphic entrapment is also greater, as strata do not generally continue updip. The prediction of Petroleum System elements in each of the three units of LST Viz., BFF, SF and LSW are summarized below:

#### *Basin Floor Fan*

Reservoirs exhibit variable thickness, areal extent and heterogeneity. They typically exhibit excellent permeability & porosity. However, the spatial continuity may vary greatly, particularly in upper channelized lobes. Migration is typically vertical from deeper sources but possibility of downward and lateral migration from condensed section shales is also high. Source rock is likely to be from deeper beds. However, Shales within the top and condensed section can also contribute if sufficiently mature. Traps are likely to be stratigraphic / morphological, lithologic and subtle. However, in well-developed fans structural entrapment may also occur due to compaction mounds. Seal integrity is usually excellent, provided by the pelagic shale of condensed section. However, when BFF is directly overlain by slope fan seal risk is high.

#### *Slope Fan*

Reservoirs are usually 5 to 40m thick sands deposited in slope in channels. They are linear in nature, dip oriented and discontinuous. Thin sands in overbank facies may be quite widespread but very thin often not more than a couple of meters thick and hence are difficult to recognize and evaluate seismically. Migration is probably vertical via fault conduits or from the downdip BFF complex if lateral connectivity is established. Source is usually from deeper sediments of the older sequences. Traps are typically stratigraphic in nature but some may be structurally enhanced along the upper slope. Seal is locally provided by the intervening shale and the top seal by condensed section. In case of Overbank sands, the lateral seal may be provided by levee banks and apron-edge pinch outs

#### *Low Stand Prograding Wedge*

Reservoir development is variable, usually present in the form of stacked fluvial, deltaic and shoreface sands. They exhibit variable thickness and continuity and are usually sand rich. Migration probably depends on fault conduits from deeper source. Possible downward migration from TST may also be present. Source rocks are usually provided by the deeper shale beds of older sequences or occasionally from the TST shales at top. Traps are typically structural nature with possible compaction closure. Seal integrity is usually very good as the immediately overlying TST shales provide goop top seal. But they may lack proper lateral seal because of the stacked nature of reservoirs.

### **Transgressive Systems Tract (TST)**

The transgressive sequence sets (TSS) in high accommodation settings are the most overlooked hydrocarbon bearing component of the sequence stratigraphic model (Posamentier, 2002b). TST's often provide lateral and top seal for LST reservoirs in the basin, when they are shale-prone, and for HST reservoirs on the shelf, when they comprise 2nd-order transgressive mud rocks. They also can contain significant source rocks facies, particularly at the second-order. When reservoirs are present, they tend to be more marine than those of the HST or LST, and thus more laterally continuous. Development of thick TST usually involves high local subsidence like in the case of growth fault wedges. Reservoir development is usually good and extensively strike aligned like Beach-shore- face deposits, long shore bars, transgressive bars etc. They generally are well winnowed due to wave and tidal action and have excellent porosity and permeability. The reservoir fairways have predictable linear trends aligned along the paleo strike forming what is known as shoe - string deposits. Migration is typically downward and laterally within TST. Source rocks are well developed within TST itself and when mature they provide excellent source. Traps are mostly stratigraphic in nature within isolated sands. Where the individual reservoirs amalgamate to form regionally continuous fairways, they require a structural entrapment

to host large pools. Seal integrity is good at top but it varies laterally and at base as the underlying LSP usually containing high sand content may prove to be leaky.

### **Highstand Systems Tract (HST)**

In hydrocarbon exploration, many of the earliest discoveries are found in updip structural traps, which tend to be dominated by reservoirs of the HST or highstand sequence set. In some high accommodation basins like West Africa or Gulf of Mexico, this scales up to the highstand sequence set level. Stratigraphic traps are less common in HSTs as strata often continue updip without significant barriers and hence are regionally "leaky". Structural closure (anticlinal or fault-type) can provide the potential for entrapment, especially if sealed by overlying shaly TST's. Reservoirs are found to be discontinuous both along and across depositional dip. Usually fluvial, deltaic facies predominate with minor shoreface facies. Younger reservoirs migrate sea ward with a typical predictability and tend to have thickening and coarsening sequences. The thickness, distribution and extent may vary depending on the sub environment and usually a well constrained stratigraphic model can be used to predict the reservoir distribution. Migration of Biogenic Gas and lean oil typically occurs from contemporaneous source. Good oil source from older sequence often requires vertical fault conduit. Source is usually deep and often a problem. HST shales prove to be lean and gas prone. Traps are predominantly structural. Early timing of structure formation is critical to host large pools. Seal Leaks updip into TST. Flooding surface usually top seal but they often leak laterally.

### **Conclusions**

The objective of this article is to expose the readers to the fundamental principles of seismic stratigraphy and its close relationship to sedimentological principles. This article also gives an overview of the Sequence Stratigraphic analysis of seismic facies, identification of Systems Tracts and inferring various Petroleum system elements for the purpose of Hydrocarbon exploration. The concept of Seismic stratigraphy techniques helps us in stratigraphic interpretation of seismic reflectors. It is important because geological concepts of stratigraphy can be applied on seismic data and hence, seismic stratigraphy can be used as a predictive tool for petroleum system elements like reservoir, seal and source rock. The basic assumption behind seismic stratigraphy is that individual reflector can be considered as chronostratigraphic surfaces i.e., it is representing a very short time interval of similar sedimentation conditions. This assumption signifies that seismic reflector can represent different depositional environments and therefore it has information of various lithofacies units. Seismic stratigraphy aims at searching for more direct seismic evidence as to the nature of the rocks and the fluid contained within their pore spaces. Seismic data resulting from optimum acquisition and processing allow for extraction of geological details beyond mere structure maps and thus give critical inputs on exploration targets even with very little or no well information. Identification of sequence boundaries in a seismic section according to specific criteria is the first step in Seismic stratigraphic analysis. In the next step, the reflection configuration in between the sequence boundaries is analyzed in detail to define systems tracts, which constitute sets of similar depositional patterns, represented by well-defined stratal patterns varying from sigmoidal to oblique, oblique to aggradational or retrogradational depositional geometries. Individual systems tracts are separated by major flooding surfaces, indicating a marked change in accommodation. A well-constrained seismic stratigraphic study including the definition of sequences and systems tracts as well as lithofacies information from well logs, results in preparation of regional gross depositional environment models and facies map, predict reservoir trends in consistency with the regional depositional setting and to infer various Petroleum System elements that result in significant mitigation of risk in firming up exploratory prospects.

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