SEISMIC STRATIGRAPHY INTERPRETATION USING SEQUENCE STRATIGRAPHY

PART 1: SEISMIC STRATIGRAPHY INTERPRETATION PROCEDURE

P. R. VAIL
Rice University
Houston, Texas

INTRODUCTION

Application of seismic stratigraphic interpretation techniques to sedimentary basin analysis has resulted in a new way to subdivide, correlate, and map sedimentary rocks. This technique is called *sequence stratigraphy*. The application of this procedure to a grid of seismic data groups seismic reflections into packages that correspond to chronostratigraphically constrained genetic depositional intervals. These intervals are called *depositional sequences* and *systems tracts*. They have predictable stratal patterns and lithofacies; thus, they provide a new way to establish a chronostratigraphic correlation framework based on physical criteria.

Depositional sequences correlate throughout sedimentary basins and probably correlate globally. Particular sets of depositional processes and thus certain depositional environments and lithofacies are associated with particular systems tracts. Thus, an identification of systems tracts on seismic data provides a framework for more accurate prediction of depositional environments and lithofacies. An accurate knowledge of depositional environments and lithofacies enables improved predictions of reservoir, source, and seal rocks and migration pathways. Fundamental control of depositional sequences, is, we believe, short-term eustatic changes of sea level superimposed on longer-term tectonic changes. Systems tracts also provide a seismic target that is thicker than an individual reservoir unit, but which has a genetic relationship to that reservoir unit. This genetic relation between systems tracts and reservoir units makes the seismic prediction of reservoirs more dependable.

This chapter describes the procedure for predicting stratigraphy from seismic data using the seismic expression of sequences and systems tracts. It first discusses the relation of seismic reflections to geologic time lines and shows how this relationship provides the basis for subdividing seismic reflections into packages corresponding to genetic depositional intervals. Following this, the genetic intervals are discussed in the section on sequence stratigraphy. The section on seismic sequence analysis describes how these genetic depositional intervals are interpreted from seismic data. The section on seismic facies shows how a seismic facies analysis of these genetic intervals is more accurate because of the association of particular systems tracts with particular depositional processes. The specific ages of the depositional sequences and systems tracts for the Mesozoic and Cenozoic are presented on a chart (Plate 1) that shows global cycles of relative changes of coastal onlap and eustatic changes of sea level related to biostratigraphic zonations, magnetic reversals, and absolute age dates.

The seismic sections in this volume that were prepared by some of the authors of this paper illustrate the application of this interpretation procedure to predicting stratigraphy from seismic data. Other sections provide a test of the method.

SEISMIC STRATIGRAPHY INTERPRETATION PROCEDURE

The seismic stratigraphy interpretation procedure recommended in this report consists of seven steps. They are:

1—seismic sequence analysis
2—well-log sequence analysis
3—synthetic, well-to-seismic ties
4—seismic facies analysis
5—interpretation of depositional environment and lithofacies
6—forward seismic modeling
7—final interpretation

The first step is 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; three patterns, truncation, toplap, and apparent truncation, occur below the discontinuity. These patterns are shown on Figure 1 and are discussed more fully later in this chapter in the section on seismic sequence interpretation. Sequence boundaries are characterized by regional onlap and truncation. With one exception, systems tract boundaries within a sequence are characterized by regional downlap.

The second step is 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 shown on Plate 1; and by correlation with seismic profiles.

The third step is synthetic well-to-seismic ties. 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. Figure 2 is an example of a synthetic seismogram that accomplishes both of these objectives. The composite synthetic seismic trace shows how the depth information relates to seismic time, and the plots of individual wavelets show the contribution from each impedance interface to the individual reflections. We recommend that seismic sequence analysis and well-log sequence analysis be started independently so that discontinuities are identified as objectively as possible on both the seismic and well data before they are tied together by the synthetics. After the synthetic ties are completed, the sequence and systems tract boundaries can be adjusted to the best solution.

The fourth step is seismic facies analysis. Its purpose is to determine as objectively as possible all variations of seismic parameters within individual seismic sequences and systems tracts in order to determine lateral lithofacies and fluid type changes. The principal seismic parameters used in seismic facies analysis are the geometry of reflectors within sequences and systems tracts, amplitude, frequency, continuity and interval velocity. Well-processed instantaneous velocity sections are ideal for seismic facies analysis. The seismic sequence and systems tract boundaries interpreted on the basic seismic profiles should be used to identify physical discontinuities. The abrupt changes across these discontinuities should be separated from more gradual lithofacies changes within the genetic sequences and systems tracts. Log-calibrated velocity corridors for rock type prediction, offset analysis for fluid and lithofacies determination, and P/S ratios for gross rock type are other important lithofacies prediction tools in the proper setting.

The fifth step is interpretation of depositional environment and lithofacies from the objectively determined seismic facies parameters coupled with a maximum knowledge of the regional geology.

The sixth step is forward seismic modeling, which has, in general, three purposes. The first is to interpret stratigraphy and fluid composition at or near the limits of seismic resolution by wave-form analysis. Our experience indicates that this is more accurately accomplished within a depositional environment and lithofacies interpretation framework based on seismic sequence and seismic facies analysis. The second purpose is seismic simulation of a geologic cross section showing stratal surfaces and impedance contrasts. These sections are commonly made to compare with the seismic data to understand seismic response. The third purpose is simulation of the reflection patterns seen on seismic sections by calculating stratal patterns from rates of subsidence, eustasy, and sediment supply. This is called basin simulation modeling.

The seventh step is an integrated final interpretation based on the interpretation objectives and the data available.

Since the interpretations in this chapter are limited to the first five steps, the following sections will discuss them in further detail.

SEISMIC REFLECTIONS AND GEOLOGIC TIME LINES

Three types of relations between seismic reflections and geologic time lines are identifiable on seismic sections. They are (1) seismic reflections that follow synchronous geologic time lines within (plus-or-minus) one-

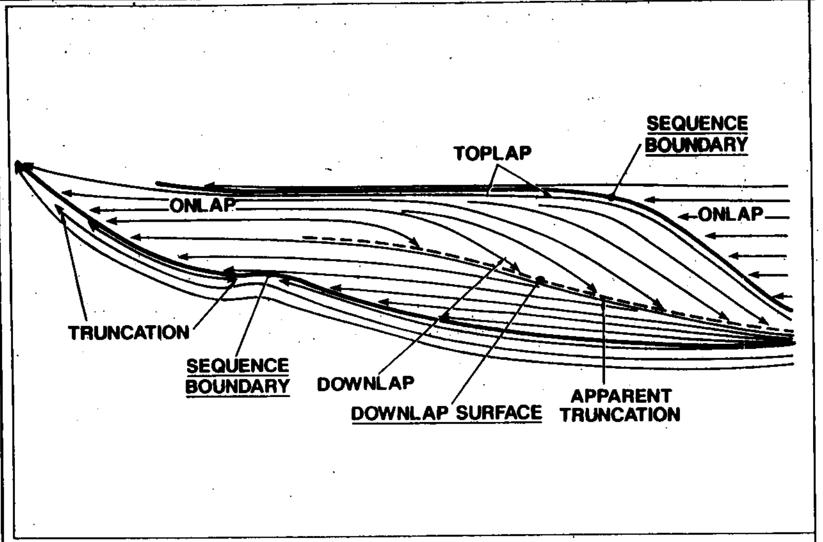


Figure 1. Diagram showing reflection termination patterns and types of discontinuities. Discontinuity names are underlined.

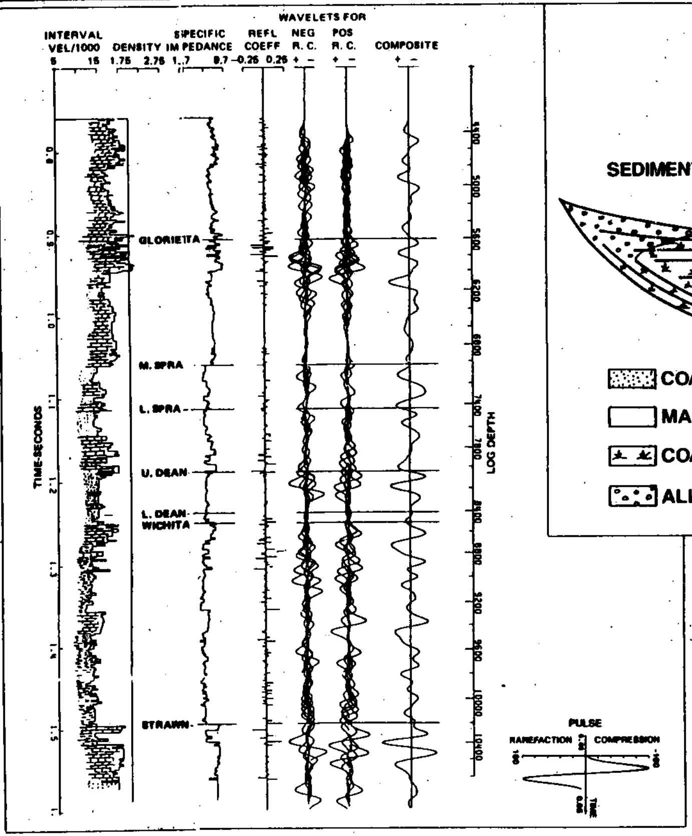


Figure 2. Synthetic seismogram from the Midland basin, Texas.

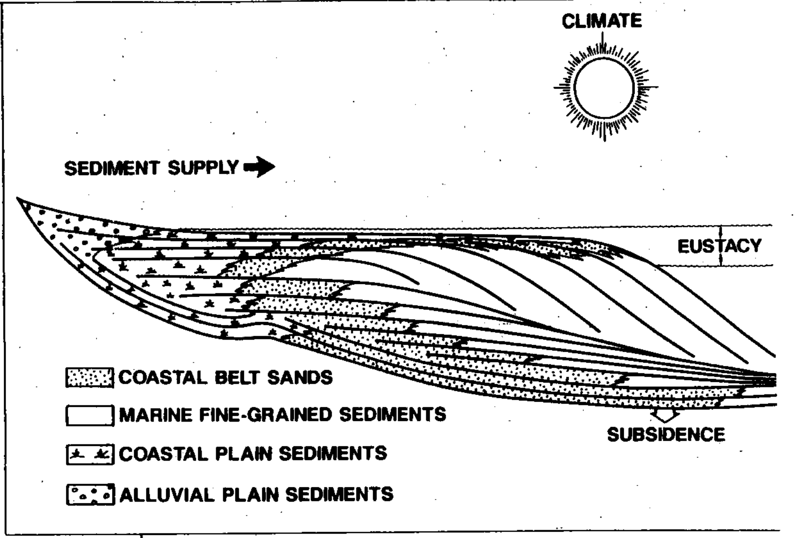


Figure 3. Diagram of seismic reflections, lithofacies, and major variables affecting stratigraphy.

half wavelength; (2) seismic discontinuities, such as unconformities and downlap surfaces, that follow geologic time boundaries; and (3) rare seismic reflections caused by fluid interfaces and certain diagenetic changes that follow surfaces that are diachronous to geologic time lines. Vail et al. (1977, part 5), discuss how seismic reflections are produced primarily from stratal surfaces and from discontinuities, such as unconformities and downlap surfaces, with sufficient velocity–density contrasts to cause coherent seismic reflections. Stratal surfaces represent ancient surfaces of deposition and therefore are essentially time synchronous. The duration of the hiatus associated with a discontinuity varies, but the discontinuity is, itself, a geologic time boundary because it separates rocks of different ages and does not cross other chronostratigraphic surfaces. For example, the ages of the strata above and below an unconformity will vary if the areal extent of erosion or non-deposition varies with time, but all the rocks below the unconformity will be older then the rocks above the unconformity. Although time lines merge along a discontinuity, none actually cross it. For these reasons, reflections derived from discontinuities are not diachronous. Diachronous reflections are caused by fluid interfaces, such as gas/water, gas/oil, and (in certain cases) oil/water; by gas hydrates; and by certain diagenetic changes, such as the opaline transition in areas where biogenic silica is plentiful.

Figure 3 shows diagrammatically the typical relationship between seismic reflections and lithofacies. The black lines represent seismic reflections. Notice how they cross lithofacies boundaries. For example, those near the top of the diagrammatic section pass from fine-grained marine shales, through nearshore sands, into coastal-plain sediments, and finally onlap as a fluvial lithofacies. The seismic reflections are following former depositional (stratal) surfaces, which are the true physical surfaces in the rocks and are not the time-transgressive lithofacies boundaries. There is no continuous physical surface at a time-transgressive lithofacies boundary for a reflection to follow. Higher amplitudes associated with the greater impedance contrasts within the zone of sand/shale interbedding, for example, typically climb from one reflection to the next as the zone of maximum impedance contrasts climbs. Because rock formation boundaries commonly follow mappable lithofacies boundaries, seismic reflections also will cross formation boundaries where they are time transgressive.

Although seismic reflections closely follow synchronous geologic time lines, bed spacing can cause the reflection peak to vary by plus-or-minus one-half the seismic wavelength. This relationship is shown on their figure 17, and discussed on page 115, of Vail et al. (1977).

Two discontinuities are also shown on Figure 3. The lower one, located near the base of the diagrammatic section, is characterized by regional onlap; it is a sequence boundary. The upper one, located in the middle of the diagrammatic section, is characterized by downlap; it is a downlap surface. Notice that the sequence boundary is located within the sand lithofacies and crosses into a coastal- plain lithofacies. The downlap surface is located within the fine-grained marine shales and passes laterally into nearshore sands and coastal-plain sediments. The location of sequence boundaries and downlap surfaces within lithofacies or formational units is common.

If the preceding discussion is true, as we contend, there is no obvious relation between seismic reflections and lithofacies. However, there is such a relation, and to understand it we must understand how the major variables of subsidence, sea level, sediment supply, and climate affect the stratal patterns and lithofacies distributions.

SEQUENCE STRATIGRAPHY

There are four major variables that control the variations in stratal patterns and lithofacies distributions within sedimentary rocks. The first is tectonic subsidence, which creates the space where the sediments are deposited. The second is eustatic change of sea level, which we believe is the major control over the stratal patterns and the distribution of lithofacies. The third is the volume of sediments, or how much of the basin is filled. It controls paleowater depth. The fourth is climate, which is a major control over the type of sediments. For example, rainfall and temperature are important to the distribution of carbonates and evaporites and to the type and amount of siliciclastic rocks deposited.

The combination of eustacy and tectonic subsidence produces a relative change of sea level. The key to understanding stratigraphy is an understanding of the relative change of sea level. Figure 4 includes a plot of eustasy against a linear plot of tectonic subsidence. We used a linear plot to match our field observations that tectonic subsidence changes slowly with respect to eustasy. The combination of eustasy and tectonic subsidence gives us the relative change of sea level. The relative change of sea level creates the accommodation, or available space, for the sediments. As is evident on Figure 4, the thickness of sediments is primarily controlled by tectonic subsidence. The depositional stratal patterns and distribution of lithofacies, however, are controlled by the rate of relative sea level change. This expresses itself by the change of slope on the relative-change-of-sea-level curve. It is controlled primarily by eustasy.

Our studies show a unique relation between the rate of relative change of sea level and depositional processes. To illustrate this, the relative-change-of-sea-level curve is subdivided into a number of time intervals. Our studies show that the discontinuities that we observe in the stratigraphic record and that bound systems tracts correspond to the vertical lines that bound the time intervals shown on Figure 4, and the systems tracts represent the rocks deposited within these time intervals. The solid black lines show where the discontinuities characterized by regional onlap and truncation plot in respect to the relative-change-of-sea-level curve; they define a sequence. A sequence is interpreted to be deposited during a cycle of eustatic change of sea level starting and ending in the vicinity of the inflection points on the falling limbs of the sea level curve.

The relationship between relative changes of sea level and systems tracts is shown in depth and geologic time on Figure 4. There are four systems tracts: lowstand, transgressive, highstand, and shelf margin. Each systems tract is identifiable on the basis of objective criteria observable in outcrops, on well logs, and on seismic data.

Lowstand systems tracts are deposited basinward of the preceding depositional shoreline break, previously called the depositional shelf edge. They overlie a Type 1 sequence boundary and lap out at (or near) the preceding depositional shoreline break, except where they fill incised valleys on the shelf, as shown on Figure 4. There are three major variations of stratal patterns associated with lowstand deposits. Figure 5a shows the case in which there is a distinct shelf–slope break and a deep-water basin. Figure 5b shows the case having no distinct shelf–slope break and with the shelf-to-basin change as a ramp. Figure 5c shows the case in which there are large growth faults associated with the shelf–slope break and the zone of growth faulting acts similarly to a depositional shoreline break.

The shelf-edge case illustrated on Figures 4 and 5a may have four parts: lowstand basin floor fan, lowstand slope fan, lowstand wedge, and incised valley fill. Lowstand basin floor fans are composed primarily of deep marine mounds made up of massive sands or carbonate debris deposited as lobes or channels. Lowstand slope fans are made up of mass flows and turbidite channel/overbank deposits. Lowstand wedges are largely composed of shallowing-upward lowstand deltas or terraces that prograde basinward and pinch out landward at the preceding depositional shoreline break. They are characterized by aggradational progradation, shown on Figure 6. Basin floor turbidites may interfinger with the toes of the lowstand wedge prograding strata in certain sand-rich systems, giving a shingled appearance. Lowstand incised valley fills are made up of sediments that fill previously cut valleys and are contemporaneous with the lowstand slope fan and lowstand wedge, or are filled later during the time when the transgressive systems tract is deposited.

The ramp case illustrated in Figure 5b may have three parts: a lower lowstand wedge, an upper lowstand wedge, and lowstand incised valley fill. The lower lowstand wedge is an interval that pinches out basinward of the preceding shoreline break and is the most basinally restricted unit. The upper lowstand wedge onlaps the lower wedge and pinches out in the vicinity of the shoreline break above the lower wedge. The lowstand incised valley fill is made up of sediments deposited contemporaneously with the upper wedge, or later during the time when the transgressive systems tract is deposited.

The growth fault case illustrated in Figure 5c usually has two parts, consisting of a thick section of lowstand interbedded sands and marine shales deposited on the downside of the growth fault and an incised valley fill. The lowstand sediments deposited on the downside of the growth fault commonly pinch out in the vicinity of the growth fault. Broad, incised valleys, commonly filled contemporaneously with the lowstand deposits, may be very common landward of the fault zone.

The boundary at the base of the lowstand systems tract is a sequence boundary. In the deep-water setting, Figure 5a, the boundaries between the units within the lowstand systems tract are downlap surfaces. The downlap surface between the lowstand basin floor fan and lowstand slope fan is called the top basin floor fan surface (Figure 4). The downlap surface between the lowstand slope fan and the lowstand wedge is called the top slope fan surface (Figure 4). In the ramp setting, the boundary between the lower and upper lowstand wedge is called the mid-lowstand surface (Figure 5b).

Transgressive systems tracts are made up of a set of backstepping, retrogradational parasequences that thicken shelfward until they thin by onlap at the base. In general, the younger parasequences in the set are progressively thinner than the older because of sediment starvation. Thus, the transgressive systems tract thins basinward and upward, forming a condensed section at the top and seaward of the inner shelf. In areas of lower sediment supply, incised valleys may not fill with sediments until the time of the transgressive systems tract.

The boundary at the base of the transgressive systems tract is the first flooding surface above the lowstand wedge systems tract. It is called the transgressive surface. Landward of where the lowstand systems tract pinches out, the lower boundary of the transgressive systems tract coincides with the unconformable part of the sequence boundary.

Highstand systems tracts are made up of three parts: early highstand, late highstand prograding complex, and late highstand subaerial complex (Figure 7). The early highstand is characterized by an upward- and outward-building sigmoidal prograding stratal pattern (Figure 6). The late highstand prograding complex is characterized by an outward-building oblique prograding stratal pattern (Figure 6); the late highstand subaerial complex is characterized by sediments deposited above sea level. The late highstand prograding complex and the late highstand subaerial complex are deposited contemporaneously. The boundary at the base of the highstand systems tract is a downlap surface that is associated with the condensed section and is called the maximum flooding surface (Figure 4). It becomes conformable on the inner shelf and loses its identity within the coastal plain sediments.

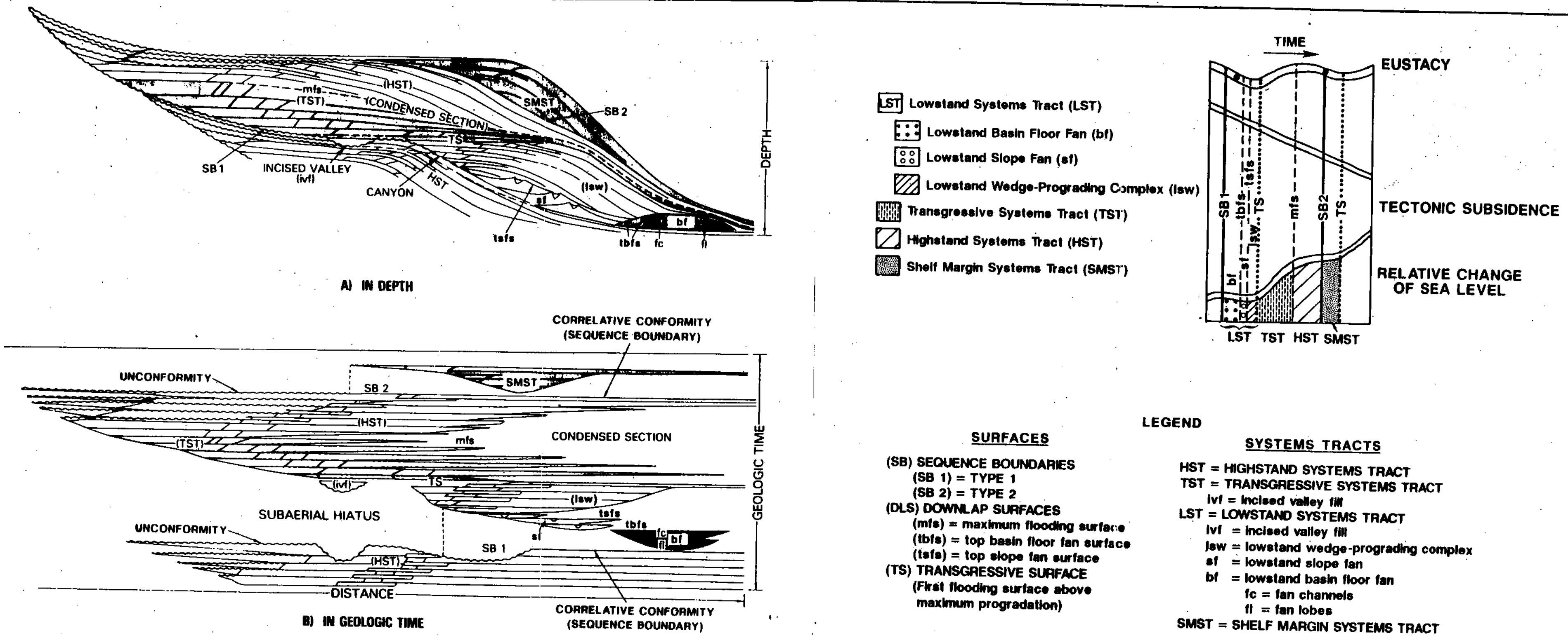


Figure 4. Sequence stratigraphy diagrammatic section, showing sequences and systems tracts in depth and geologic time.

The shelf margin systems tract is a prograding and aggrading wedge that overlies a Type 2 sequence boundary and laps out on the shelf landward of the preceding depositional shoreline break. The shelf margin prograding wedge is characterized by aggradational progradation (Figure 6). Its lower boundary is a conformable sequence boundary and its upper boundary is a transgressive surface. An unconformity exists landward of where it pinches out.

This section has described the geometry of depositional sequences and systems tracts. The next step is to interpret them on seismic data.

SEISMIC SEQUENCE ANALYSIS

The objective of seismic sequence analysis is to interpret depositional sequences and systems tracts on seismic sections by identifying discontinuities on the basis of reflection terminations. The best way to do this is to look for places where two reflectors converge. Where reflectors converge there will be reflection terminations. Mark the reflection terminations with arrows. Draw in the discontinuity surface between the onlapping and downlapping reflections above, and the truncating and toplapping reflectors below. If the discontinuity becomes conformable, trace its position across the section by reflection correlation. Continue this process on all additional lines in the grid. Close all seismic grid loops by checking the loop ties for each discontinuity or its conformable equivalent. Identify the type of discontinuity. If it is characterized by regional onlap above and truncation below, it is probably a sequence boundary. If it is characterized by regional downlap, it is most likely a downlap surface.

When analyzing seismic data, we recommend a consistent color code for tracing reflection patterns and surfaces of discontinuity. We use red for reflection patterns and reflection terminations, green for downlap surfaces (yellow for those who are color blind), blue for transgressive surfaces, and other colors for sequence boundaries. If the interpretation needs to be presented in black and white, we recommend thin solid lines for reflection patterns and thicker solid lines for sequence boundaries, dashed lines for downlap surfaces, and dotted lines for transgressive surfaces. The procedure seems deceptively simple, but it takes considerable experience to perfect it.

Figure 1 shows a simulated seismic section, and illustrates the procedure described above. Within the lower zone of convergence, reflectors terminate by lapping out in an updip direction. This is the onlap pattern. Another zone of convergence at the top of the section is also characterized by onlap. Between these zones characterized by onlap are zones of convergence characterized by reflectors that terminate by lapping out in a downdip direction. This is the downlap pattern. On the left-hand part of the diagram, reflectors terminate upward below the discontinuity and indicate that a section is missing. Two examples are shown: the eroded top of a structure, and regional beveling. This is the truncation pattern. On the upper right-hand portion of the diagram, the reflectors lap out against each other below the discontinuity. This is the toplap pattern. In the right center, reflectors terminate below the discontinuity by depositional thinning (sediment starvation). This is the apparent truncation pattern.

In summary, there are two types of reflection termination patterns that lap out above the discontinuity. These are onlap and downlap. Three types of reflection termination patterns terminate below the discontinuity: truncation, toplap, and apparent truncation. In cases where highstands are thick, toplap may occur well below the sequence boundary, as shown on Figure 1. Care must be taken to identify onlap above the discontinuity to be sure of the position of the sequence boundary. An additional reflection termination pattern that does not indicate a discontinuity is divergence. Reflection terminations caused by divergence may be misleading when interpreting discontinuities.

Figure 1 also indicates the types of discontinuities. Discontinuities characterized by onlap and truncation are sequence boundaries, and are marked with solid lines. The discontinuities characterized by downlap are downlap surfaces; they are marked with dashed lines. Three types of downlap surfaces are shown: top basin floor fan surface, top slope fan surface, and maximum flooding surface commonly associated with a condensed section. Transgressive surfaces are the most difficult to identify on seismic data. If a depositional shoreline break is present, the transgressive surface is commonly indicated by a high-amplitude reflector that occurs at the top of a set of offlapping reflectors and that onlaps out in a landward direction near the depositional shelf break. It is marked with a dotted line.

SEISMIC FACIES ANALYSIS

The objective of seismic facies analysis is to quantify and interpret seismic parameter variations caused by geologic changes within seismic sequences and systems tracts. The most useful seismic parameters are discussed in the previous section on interpretation procedure. In this chapter, only the reflection pattern geometries will be considered. Some of the more common patterns are shown on Figure 8.

The best way to identify reflection pattern geometries is to look for reflectors that dip at a greater angle than those above and below. In general, these reflectors will indicate depositional slopes. This pattern is called offlap. The rollover at the top of the offlap pattern indicates the depositional shelf break. Seaward of the depositional coastal break is deeper water. Deep water preserves depositional topography. Many seismic reflection patterns have been identified on seismic data recorded where the sediments were deposited in deep-water settings.

Some of the most important seismic reflection patterns are offlap, submarine onlap, submarine mounds, channel/overbank complexes, slumps, slope-front-fill, climbing toplap, and drape. The offlap pattern can be used to interpret paleowater depths by analyzing the height of the prograding clinoforms. The onlap pattern helps to interpret submarine topography. Mounds, channel/overbank complexes (leveed channel deposits), and slumps indicate lowstand deposits. Slope-front-fill generally indicates distal mudstones. Climbing toplap is often associated with deep marine current deposits. Drape indicates sediments derived from suspension. The apparent truncation and downlap patterns indicate sediment starvation. Landward of the shelf edge, seismic facies interpretation is much more difficult because sea level and stream gradients tend to level out depositional surfaces, causing parallel to subparallel seismic reflection patterns. Within this area, truncation, subtle onlap, and mounded fluvial deposits create most of the stratal geometries. Figure 6 simulates a seismic section and shows the seismic reflection patterns mentioned above. Sequence boundaries are shown as solid lines and downlap surfaces as dashed lines.

LITHOFACIES INTERPRETATION AND EXPLORATION SIGNIFICANCE

Once the more objective seismic facies interpretation procedure is completed, the more subjective lithofacies interpretation is ready to begin. The first step is to learn as much as possible about the regional geology from well and outcrop control. With this background, one needs to decide whether the sedimentary section of interest is siliciclastics, carbonates, mixed siliciclastics and carbonates, or carbonates and evaporites.

Figures 7 and 8 illustrate typical distributions of siliciclastic and carbonate lithologies in relation to depositional sequences and systems tracts. The example shown on Figure 9 is from a mixed siliciclastic and carbonate area. A first-pass interpretation based on reflection patterns alone would be that the lowstands are mainly siliciclastic and transgressive, and highstands are carbonate. If this is the case we would interpret the fan mounds as deep marine sand. The channel/overbank complexes commonly are fine-grained turbidites with sands possibly present at their apexes. The lowstand wedge prograding complex generally shallows upward and commonly has sands at the top and landward of the shelf edge. The transgressive systems tract may consist of carbonate pinnacles and banks building up on the shelf. The highstand would probably consist of shelf carbonates, slope carbonates, and basin carbonates, depending on their relation to the offlap pattern. Such an interpretation is, of course, very preliminary, but does provide a model to test with more quantitative seismic facies analysis and modeling.

Lowstand Systems Tract

The major siliciclastic lithofacies and their exploration significance within a lowstand systems tract are shown on Figure 10. Reservoir-quality sands are present in six possible positions within the lowstand systems tract. They are the mounded basin floor fan, the thin overbank turbidite sands and generally more massive channel sands of the slope fan, the shingled toe-of-slope sands and shallow-water coastal sands of the lowstand prograding complex, and the incised valley fill.

Mounded basin floor fan sands are excellent reservoirs and form many major fields. Traps are both structural and stratigraphic. Because the sands are deposited largely by turbidity currents, which flow toward basin lows, these sands will thin or pinch out against contemporaneous highs. Structural traps should have formed following deposition of the sands, in order to contain good reservoir rocks. Stratigraphic traps depend on the top and base seal. In general, the slope fan that commonly overlies the basin floor fan is not a seal because of the thin overbank turbidite sands that are commonly present. Therefore, the best stratigraphic traps pinch out in a basin direction against a contemporaneous structure or the opposite side of the basin. Basin floor fan sand pinchouts in a proximal direction usually do not trap hydrocarbons because the hydrocarbons appear to leak upward into the slope fan turbidites.

In general, the first possible seal is the prograding toes of the lowstand prograding wedge. Thus, the top fan surface should show closure or pinch out to develop a trap. In areas where the lowstand prograding wedge onlaps in a proximal direction instead of downlapping, it probably will not seal because of the presence of coastal sands.

The turbidite sands of the slope fan contain major hydrocarbon reserves, but the reservoir properties of the thin overbank turbidites are poor. Sands within the channels of the slope fan commonly are excellent reservoirs, but are very difficult to predict ahead of the drill unless they contain a seismic hydrocarbon indicator. The first overlying sealing rock is usually the prograding toes of the overlying lowstand prograding wedge, as discussed above.

The lowstand prograding wedge may contain both deep- and shallow-water reservoir sands. If the depositional system is very sandy, basin floor turbidites may be present that interfinger with the toes of the prograding clinoforms. These sands generally are turbidites that contain the complete Bouma sequence, but commonly they have well-developed basal sands that create moderately good reservoirs. The individual sands tend to be shingled and have good seals, because they pinch out between the toes of the lowstand prograding complex.

Excellent reservoir-quality shallow-water coastal sands and incised valley sands are usually present in the proximal position of the lowstand prograding

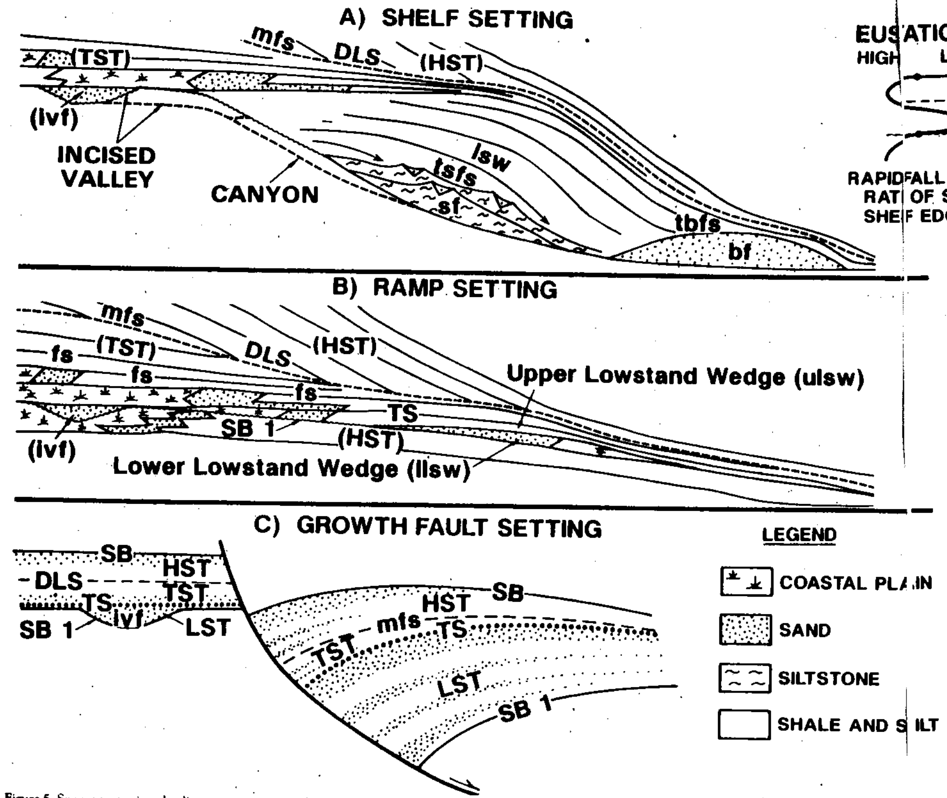


Figure 5. Sequence stratigraphy diagrammatic section, showing lowstand systems tracts in shelf, ramp and growth fault settings.

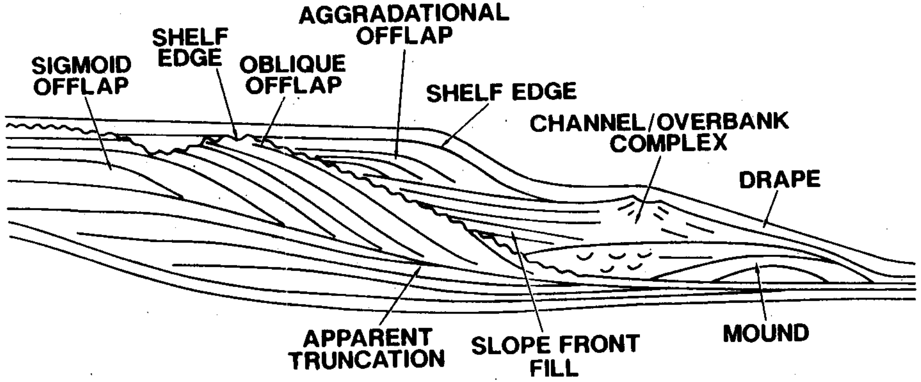
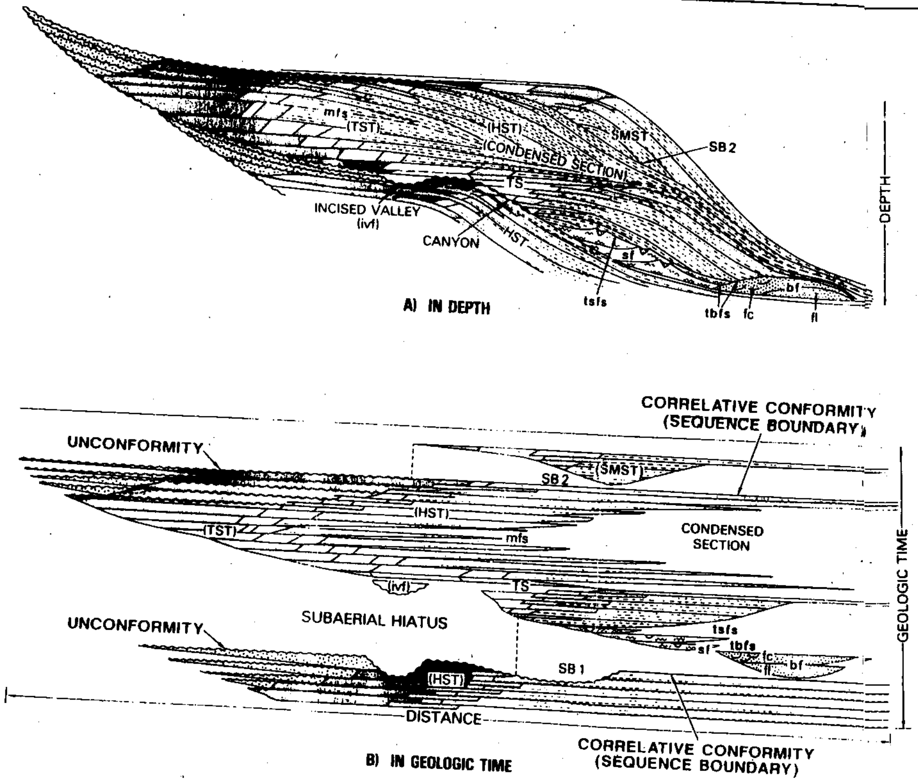


Figure 6. Diagram showing simulated seismic section with common seismic facies patterns.



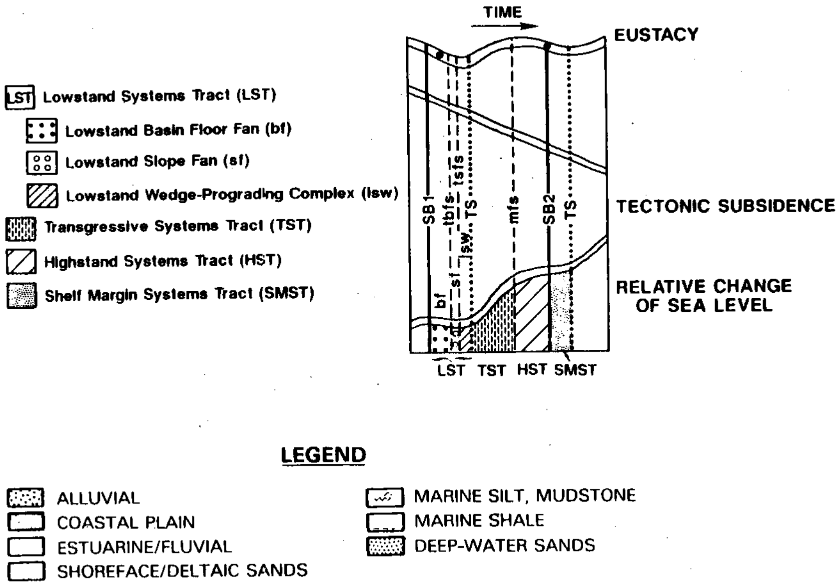


Figure 7. Sequence stratigraphy diagrammatic section, showing typical distribution of siliciclastic sediments within sequences and systems tracts in depth and geologic time.

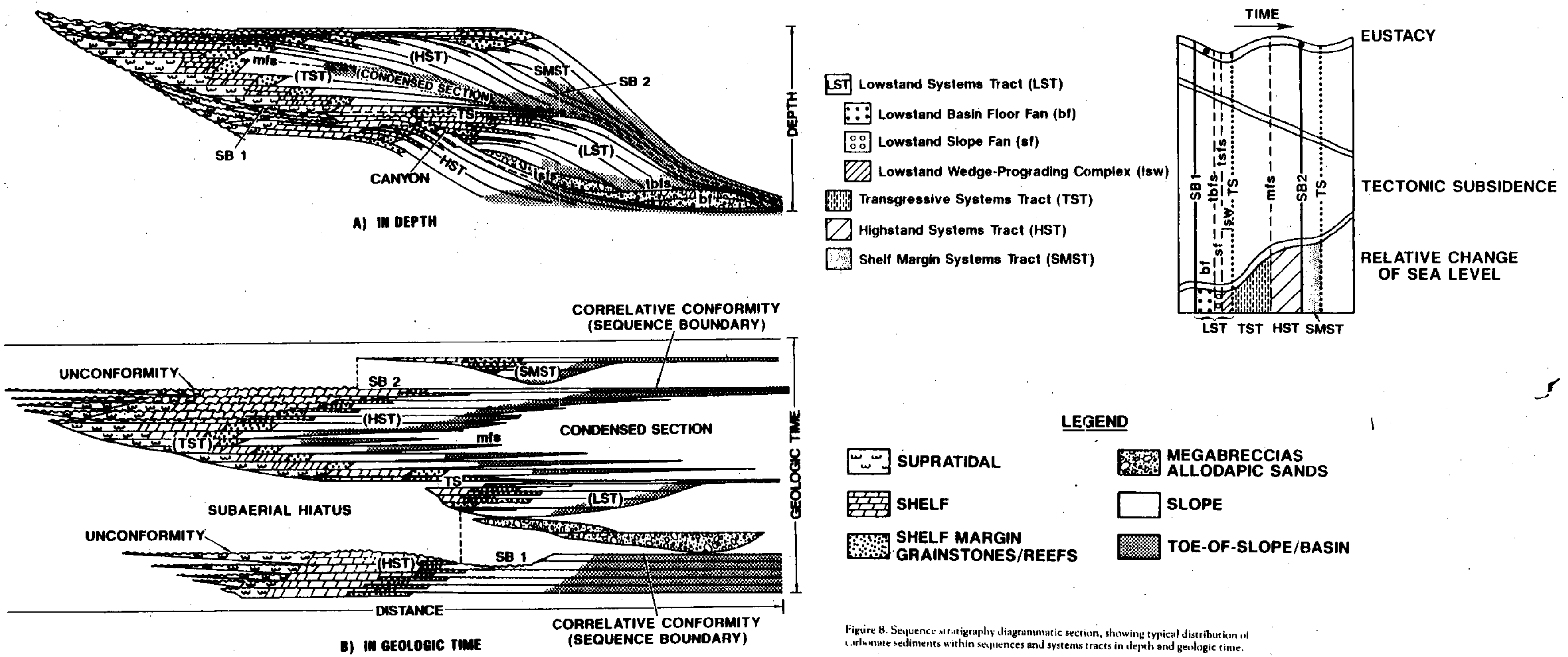


Figure 8. Sequence stratigraphy diagrammatic section, showing typical distribution of carbonate sediments within sequences and systems tracts in depth and geologic time.

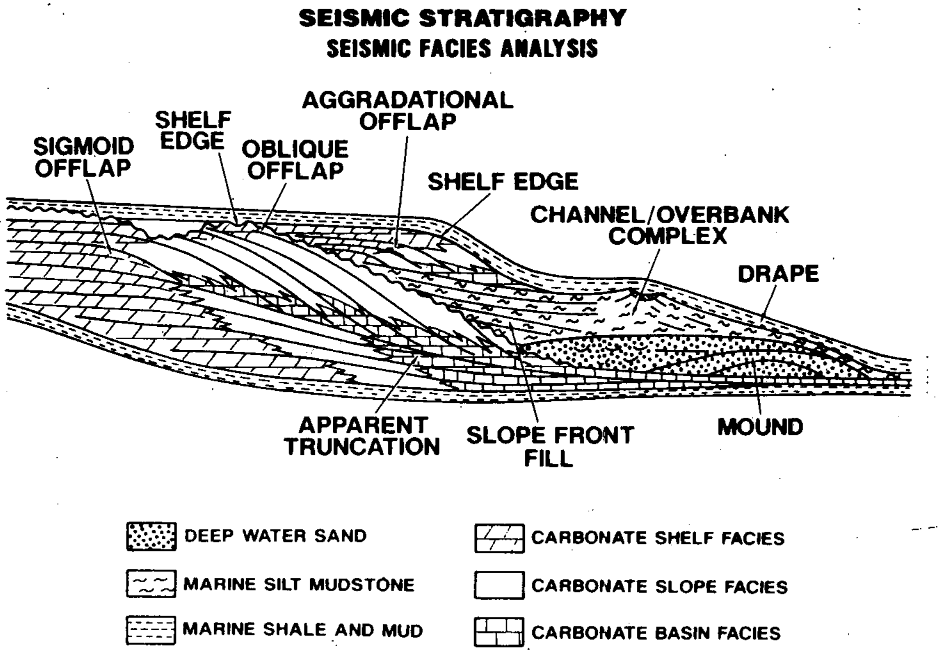


Figure 9. Diagram showing simulated seismic section with lithofacies interpretation made from seismic facies patterns.

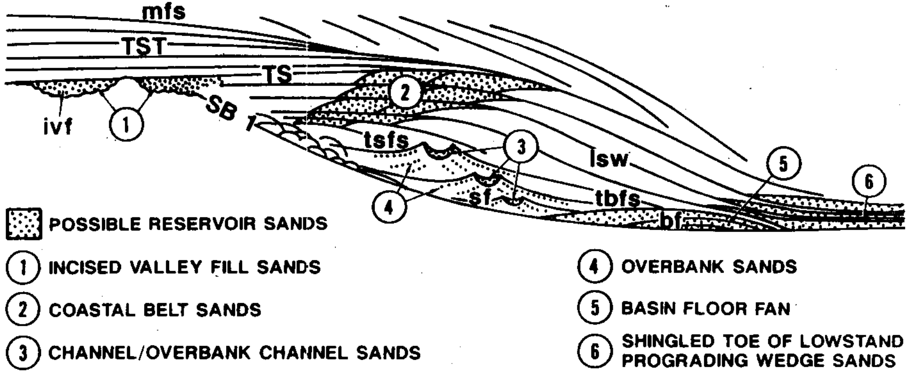


Figure 10. Diagram showing possible sand occurrences within lowstand systems tract in a deep-water basin with a well-developed shelf-slope break.

PART 2: KEY DEFINITIONS OF SEQUENCE STRATIGRAPHY

J. C. VAN WAGONER
R. M. MITCHUM, JR.
H. W. POSAMENTIER
Exxon Production Research Company
Houston, Texas
and
P. R. VAIL
Rice University
Houston, Texas

It is important to establish the fundamental concepts of *sequence stratigraphy* and to define terminology critical for the communication of these concepts. Vail et al. (1977) published *seismic stratigraphy* concepts in the American Association of Petroleum Geologists' Memoir 26. Since that time, with new insight from computer-simulation studies, outcrop documentation, and subsurface studies based on well-log and seismic control, our ideas have evolved beyond Memoir 26. These ideas are summarized here, and are presented and documented in more detail in the Society of Economic Paleontologists and Mineralogists Special Publication, *Sea-Level Change—An Integrated Approach*, scheduled to be released in 1988. In the Special Publication, an expanded version of this paper serves as the introduction for a series of eight papers documenting, with well-log, core, outcrop, and seismic examples, the concepts of sequence stratigraphy. The reader is referred to that special publication for the details of these concepts.

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities. The fundamental unit of sequence stratigraphy is the *sequence*, which is bounded by unconformities and their correlative conformities. A sequence can be subdivided into *systems tracts*, which are defined by their position within the sequence and by the stacking patterns of *parasequence sets* and *parasequences* bounded by marine-flooding surfaces. Boundaries of sequences, parasequence sets, and parasequences provide a chronostratigraphic framework for correlating and mapping sedimentary rocks. Sequences, parasequence sets, and parasequences are defined and identified by the physical relationships of strata, including the lateral continuity and geometry of the surfaces bounding the units, vertical and lateral stacking patterns, and the lateral geometry of the strata within these units. Absolute thickness, the amount of time during which they form, and interpretation of regional or global origin are not used to define sequence-stratigraphic units.

Sequences and their stratal components are interpreted to form in response to the interaction between the rates of eustasy, subsidence, and sediment supply. These interactions can be modeled and the models verified by observations to predict stratal relationships and to infer ages in areas where geological data are limited.

The paragraphs below define and briefly explain the terms important for communicating sequence-stratigraphy concepts. The terms are more fully discussed in Part 1.

Parasequences and parasequence sets are the fundamental building blocks of sequences.

- *Parasequence*—a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces (Van Wagoner, 1985). Parasequences are progradational and therefore the beds within parasequences shoal upward.

- *Marine-flooding surface*—a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth. This deepening commonly is accompanied by minor submarine erosion (but no subaerial erosion or basinward shift in facies) and nondeposition, and a minor hiatus may be indicated. Onlap of overlying strata onto a marine-flooding surface does not occur unless this surface is coincident with a sequence boundary. Marine-flooding surfaces are planar and commonly exhibit only very minor topographic relief ranging from several inches to tens of feet, with several feet being most common. The marine-flooding surface commonly has a correlative surface in the coastal plain and a correlative surface on the shelf. Facies analysis of the strata across the correlative surfaces usually does not indicate a significant change in water depth; often, the correlative surfaces in the coastal plain or on the shelf can be identified only by correlating updip or downdip from a marine-flooding surface.

- *Parasequence set*—a succession of genetically related parasequences which form a distinctive stacking pattern that is bounded, in many cases, by major marine-flooding surfaces and their correlative surfaces (Van Wagoner, 1985). Parasequence set boundaries (1) separate distinctive parasequence stacking patterns; (2) may be coincident with sequence boundaries; and (3) may be downlap surfaces and boundaries of systems tracts. Stacking patterns of parasequences in parasequence sets (Figure 1) are progradational, retrogradational, or aggradational, depending upon the ratio of depositional rates to accommodation rates. These stacking patterns are predictable within a sequence.

Sequences are the basic stratal units used to construct a sequence-stratigraphic framework within which chronostratigraphic and lithostratigraphic correlations can be done. Sequences can be recognized in well logs, cores, outcrops, or seismic lines.

- *Sequence*—a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Mitchum, 1977).

- *Unconformity*—a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated. This definition restricts the usage of the term unconformity to surfaces marked by subaerial exposure on their landward portions and modifies the definition of unconformity used by Mitchum (1977). He defines an unconformity as "a surface of erosion or nondeposition that separates younger strata from older rocks and represents a significant hiatus" (p. 211). This earlier, broader definition encompasses both subaerial and submarine surfaces and does not sufficiently differentiate between sequence and parasequence boundaries. Local, contemporaneous erosion and deposition associated with geological processes, such as point-bar development or dune migration, are excluded from the definition of unconformity used here.

- *Conformity*—a surface separating younger from older strata, along which there is no evidence of erosion (either subaerial or submarine), or nondeposition, and along which no significant hiatus is indicated. It includes surfaces onto which there is very slow deposition, with long periods of geologic time represented by very thin deposits.

Type-1 and Type-2 sequences are recognized in the rock record.

- *Type-1 sequence*—a sequence (Figures 2 and 3) bounded below by a Type-1 sequence boundary and above by a Type-1 or a Type-2 sequence boundary.

- *Type-2 sequence*—a sequence (Figure 4) bounded below by a Type-2 sequence boundary and above by a Type-1 or a Type-2 sequence boundary.

- *Type-1 sequence boundary*—a regional surface (Figures 2 and 3) characterized by subaerial exposure and concurrent subaerial erosion associated with stream rejuvenation, a basinward shift of facies, a downward shift in coastal onlap, and onlap of overlying strata. As a result of the basinward shift in facies, nonmarine or very shallow-marine rocks, such as braided-stream or estuarine sandstones above a sequence boundary, may directly overlie deeper water marine rocks, such as lower-shoreface sandstones or shelf mudstones below a boundary, with no intervening rocks deposited in intermediate depositional environments. A typical well-log response produced by a basinward shift in facies marking a sequence boundary is illustrated in Figure 2. A Type-1 sequence boundary is interpreted to form when the rate of eustatic fall exceeds the rate of basin subsidence at the depositional-shoreline break, producing a relative fall in sea level at that position. The depositional-shoreline break is a position on the shelf, landward of which the depositional surface is at or near base level (usually sea level), and seaward of which the depositional surface is below base level (Posamentier et al., in press). This position coincides approximately with the seaward end of the stream-mouth bar in a delta or with the upper shoreface in a beach. In previous publications (Vail and Todd, 1981; Vail et al., 1984), the depositional-shoreline break has been referred to as the shelf edge. In many basins, the depositional-shoreline break may be 100 miles or more landward of the shelf break, which is marked by a change in dip from gently dipping shelf (commonly less than 1:1000) landward of the shelf break to the more steeply dipping slope (commonly greater than 1:40) seaward of the shelf break (Heezen et al., 1959). In other basins, the depositional-shoreline break may be at the shelf break.

- *Type-2 sequence boundary*—a regional surface (Figure 4) marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional-shoreline break; however, it lacks both subaerial erosion associated with stream rejuvenation and a basinward shift in facies. Onlap of overlying strata landward of the depositional-shoreline break also marks a Type-2 sequence boundary. A Type-2 sequence boundary is interpreted to form when the rate of eustatic fall is less than the rate of basin subsidence at the depositional-shoreline break, so that no relative fall in sea level occurs at this shoreline position.

Sequences can be subdivided into systems tracts.

- *Systems tract*—a linkage of contemporaneous depositional systems (Brown and Fisher, 1977). We use the term, systems tract, to designate three subdivisions within each sequence: lowstand, transgressive, and highstand systems tracts in a Type-1 sequence (Figures 2 and 3), and complex. This is the position of the lowstand delta. The lowstand deltas tend to have a point source; thus, the sands are concentrated in the source areas and change facies to silts and shales both laterally and basinward. Because lowstand prograding sands tend to aggrade as well as prograde, they commonly are very thick. These sands form major reservoirs in many areas. Structural trap type varies, but rollover into a growth fault is a common trap type. Stratigraphic traps depend on an updip seal, and hydrocarbons commonly leak landward into the incised valley fill. However, if the underlying unit is impermeable, stratigraphic traps can be present where the onlapping sands pinch out below the preceding depositional shoreline break.

Fluvial and estuarine sands of the incised valleys commonly are excellent reservoirs and are excellent stratigraphic trap targets where the valleys are incised into impermeable coastal plain shales. Where shale-filled submarine canyons are developed, stratigraphic traps commonly form where older reservoir sands are truncated by the submarine canyon.

Because of the generally high depositional rates of the lowstand systems tracts, the source potential usually is low. Exceptions occur where the depositional sites are euxinic, but the percent of total organic matter seldom exceeds 1%.

Transgressive, Highstand and Shelf Margin Systems Tracts

Some of the best coastal sand reservoir rocks form when accommodation is increasing rapidly. The transgressive, early highstand, and shelf margin systems tracts all have high accommodation rates and are characterized by the development of excellent reservoir sands. These sands form the reservoirs of many major structural traps. The overlying shales of the upper transgressive systems tract and lower highstand form seals that generally are excellent at least on the outer shelf, but the updip and base seals commonly are a problem for stratigraphic traps. Stratigraphic traps do occur where seals are present over beach ridge mounds, onlapping sands, and unconformity truncations. Siliciclastic rocks of the late highstand systems tracts commonly form poorer reservoirs.

The starved portion of the transgressive and early highstand systems tract is the stratigraphic position of many of the world's best source rocks deposited in a marine environment. Coals and terrestrial source rocks also tend to be associated with the transgressive and early highstand systems tracts landward of the coastline.

GLOBAL CYCLE CHARTS

The development of sequence stratigraphic concepts has produced the basis for identifying global sea level fluctuations in subsurface seismic and well data, and in outcrops of marine sediments along continental margins and interiors. Such documentation of sea level events, especially from the outcrop sections from different parts of the world, has led to a new generation of Mesozoic and Cenozoic global cycle charts with greater resolution than that obtainable from seismic and well data alone (Plate 1).

These cycle charts are tied to a widely applicable, integrated chronostratigraphy that combines state-of-the-art geochronologic, magnetostratigraphic, and biostratigraphic data. For a more detailed discussion of these charts, see Haq et al. (1987 and in press). The charts are presented in this volume at large scale to facilitate their use in seismic stratigraphic interpretation.

ACKNOWLEDGMENT

I sincerely thank my former colleagues at Exxon Production Research Co. with whom I worked for many years. Many of the ideas and concepts presented in this report were developed by these people. Much of their work is published in a series of articles listed in the references at the end of this chapter. I especially want to acknowledge the contributions to this report by J. F. Sarg, R. M. Mitchum, Jr., S. M. Greenlee, R. D. Erskine, H. W. Posamentier, J. C. Van Wagoner, B. U. Haq and J. Hardenbol.

shelf-margin, transgressive, and highstand systems tracts in a Type-2 sequence (Figure 4).

- *Depositional system*—a three-dimensional assemblage of lithofacies (Fisher and McGowan, 1967).

Systems tracts are defined objectively on the basis of types of bounding surfaces, their position within a sequence, and parasequence and parasequence-set stacking patterns. Systems tracts are also characterized by geometry and facies associations. When referring to systems tracts, the terms lowstand and highstand are not meant to imply a unique period of time or position on a cycle of eustatic or relative change of sea level. The actual time of initiation of a systems tract is interpreted to be a function of the interaction between eustasy, sediment supply, and tectonics.

The lowermost systems tracts is called the *lowstand systems tract* (Figures 2 and 3) if it lies directly on a Type-1 sequence boundary; however, it is called the *shelf-margin systems tract* if it lies directly on a Type-2 boundary (Figure 4).

The lowstand systems tract, if deposited in a basin with a shelf break (Figure 2), generally can be subdivided into three separate units, a basin-floor fan, a slope fan, and a lowstand wedge.

- *Basin-floor fan*—a portion of the lowstand systems tract characterized by deposition of submarine fans on the lower slope or basin floor. Fan formation is associated with the erosion of canyons into the slope and the incision of fluvial valleys into the shelf. Siliciclastic sediment bypasses the shelf and slope through the valleys and the canyons to feed the basin-floor fan. The base of the basin-floor fan (coincident with the base of the lowstand systems tract) is the Type-1 sequence boundary; the top of the fan is a downlap surface.

- *Slope fan*—a portion of the lowstand systems tract characterized by turbidite and debris-flow deposition on the middle or the base of the slope. Slope-fan deposition can be coeval with the basin-floor fan or with the early portion of the lowstand wedge. The top of the slope fan is a downlap surface for the middle and upper portions of the lowstand wedge.

- *Lowstand wedge*—a portion of the lowstand systems tract characterized on the shelf by incised-valley fill (Figures 2 and 3), which commonly onlaps onto the sequence boundary, and on the slope by progradational fill with wedge geometry overlying and commonly downlapping onto the basin-floor fan or the slope fan. Lowstand wedge deposition is not coeval with basin-floor deposition. Lowstand wedges are composed of progradational to aggradational parasequence sets. The top of the lowstand wedge, coincident with the top of the lowstand systems tract, is a marine-flooding surface called the transgressive surface (Figures 2 to 4).

- *Transgressive surface*—the first significant marine-flooding surface across the shelf within the sequence.

The lowstand systems tract, if deposited in a basin with a ramp margin (Figure 3), consists of a relatively thin lowstand wedge that may contain two parts. The first part is characterized by stream incision and sediment bypass of the coastal plain interpreted to occur during a relative fall in sea level during which the shoreline steps rapidly basinward until the relative fall stabilizes. The second part of the wedge is characterized by a slow relative rise in sea level, the infilling of incised valleys, and continued shoreline progradation, resulting in a lowstand wedge composed of incised-valley-fill deposits updip and one or more progradational parasequence sets downdip. The top of the lowstand wedge is the transgressive surface; the base of the lowstand wedge is the lower sequence boundary.

- *Shelf-margin systems tract*—the lowermost systems tract associated with a Type-2 sequence boundary (Figure 4). This systems tract is characterized by one or more weakly progradational to aggradational parasequence sets; the sets onlap onto the sequence boundary in a landward direction and downlap onto the sequence boundary in a basinward direction. The top of the shelf-margin systems tract is the transgressive surface, which also forms the base of the transgressive systems tract. The base of the shelf-margin systems tract is a Type-2 sequence boundary.

- *Transgressive systems tract*—the middle systems tract of both Type-1 and Type-2 sequences (Figures 2 to 4). It is characterized by one or more retrogradational parasequence sets. The base of the transgressive systems tract is the transgressive surface at the top of the lowstand or shelf-margin systems tracts. Parasequences within the transgressive systems tract onlap onto the sequence boundary in a landward direction and downlap onto the transgressive surface in a basinward direction. The top of the transgressive systems tract is the downlap surface.

- *Downlap surface*—a marine-flooding surface onto which the toes of prograding clinoforms in the overlying highstand systems tract downlap. This surface marks the change from a retrogradational to an aggradational parasequence set and is the surface of maximum flooding. The condensed section (Figures 2 to 4) occurs largely within the transgressive and distal highstand systems tracts.

- *Condensed section*—a facies consisting of thin marine beds of hemipelagic or pelagic sediments deposited at very slow rates. Condensed sections are most extensive during the time of regional transgression of the shoreline.

- *Highstand systems tract*—the upper systems tract in either a Type-1 or a Type-2 sequence (Figures 2 to 4). This systems tract is commonly widespread on the shelf, and may be characterized by one or more aggradational parasequence sets that are succeeded by one or more progradational parasequence sets with prograding clinoform geometries. Parasequences within the highstand systems tract onlap onto the sequence boundary in a landward direction and downlap onto the top of the transgressive or lowstand systems tracts in a basinward direction. The highstand systems tract is bounded at the top by a Type-1 or Type-2 sequence boundary and at the bottom by the downlap surface.

Systems tracts are interpreted to be deposited during specific increments of the eustatic curve (Jervey, in press; Posamentier et al., in press).

- *Lowstand fan of lowstand systems tract*—during a time of rapid eustatic fall;

- *Slope fan of lowstand systems tract*—during the late eustatic fall or early eustatic rise;

- *Lowstand wedge of lowstand systems tract*—during the late eustatic fall or early rise;

- *Transgressive systems tract*—during a rapid eustatic rise; and

- *Highstand systems tract*—during the late part of a eustatic rise, a eustatic stillstand, and the early part of a eustatic fall.

The subdivision of sedimentary strata into sequences, parasequences, and systems tracts provides a powerful methodology for the analysis of time and rock relationships in sedimentary strata. Sequences and sequence boundaries subdivide sedimentary rocks into genetically related units bounded by surfaces with chronostratigraphic significance. These surfaces provide a framework for correlating and mapping. Interpretation of systems tracts provides a framework for predicting facies relationships within the sequence. Parasequence sets, parasequences, and their bounding surfaces further subdivide the sequence and component systems tracts into smaller genetic units for detailed mapping, correlating, and interpreting depositional environments.

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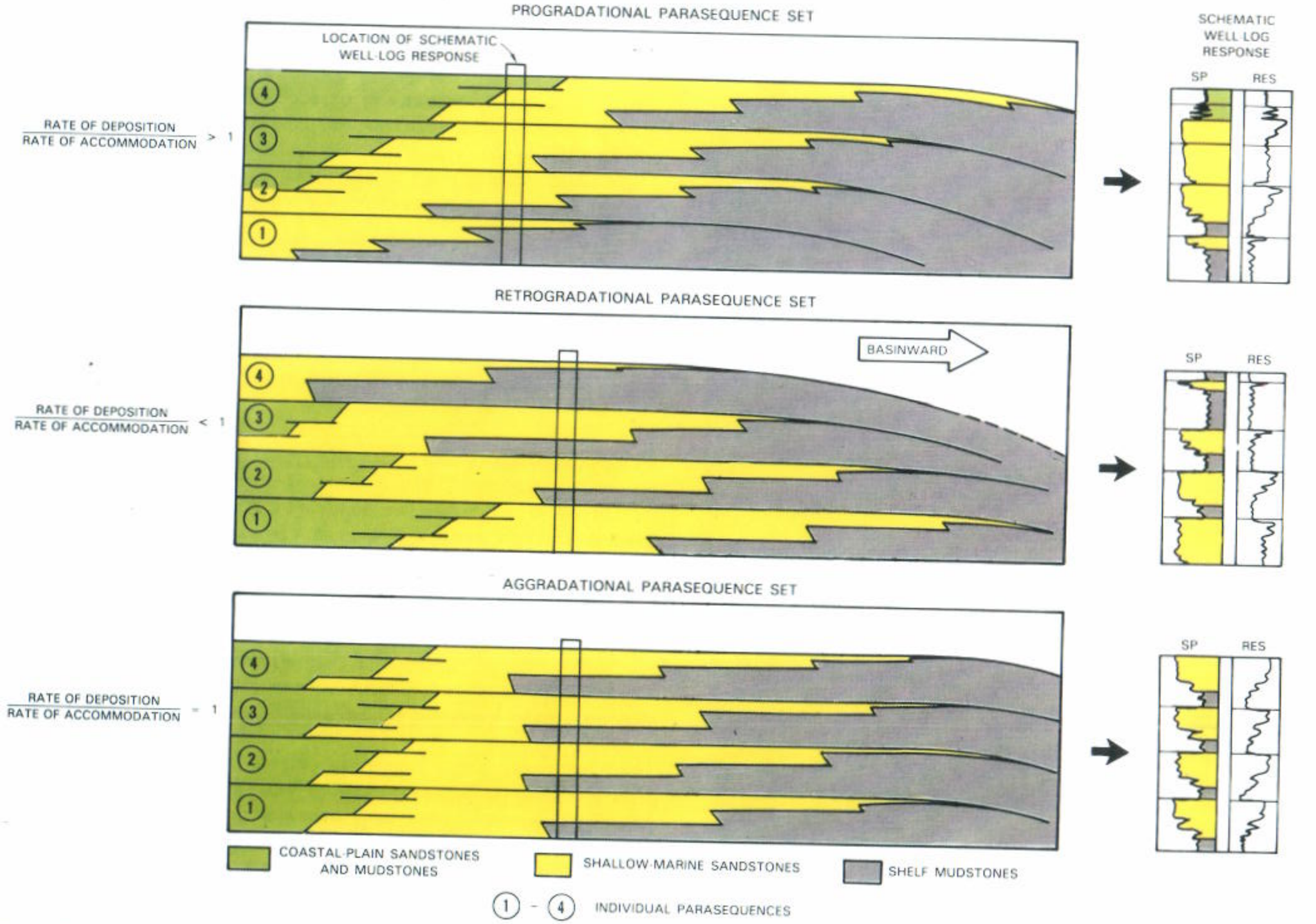

Figure 1. Parasequence stacking patterns in parasequence sets; cross section and well-log expression.

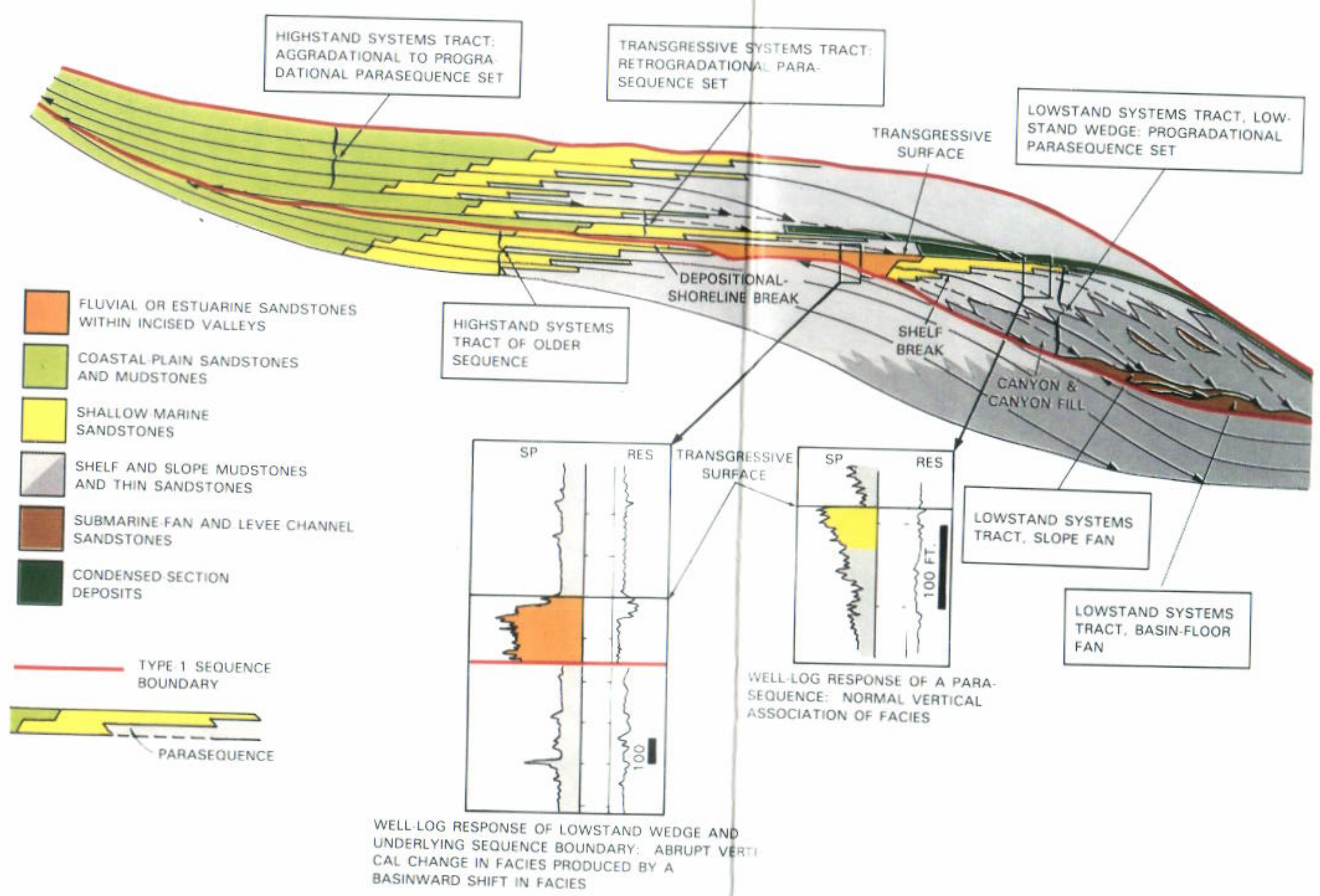

Figure 2. Stratal patterns in a Type-1 sequence deposited in a basin with a shelf break.

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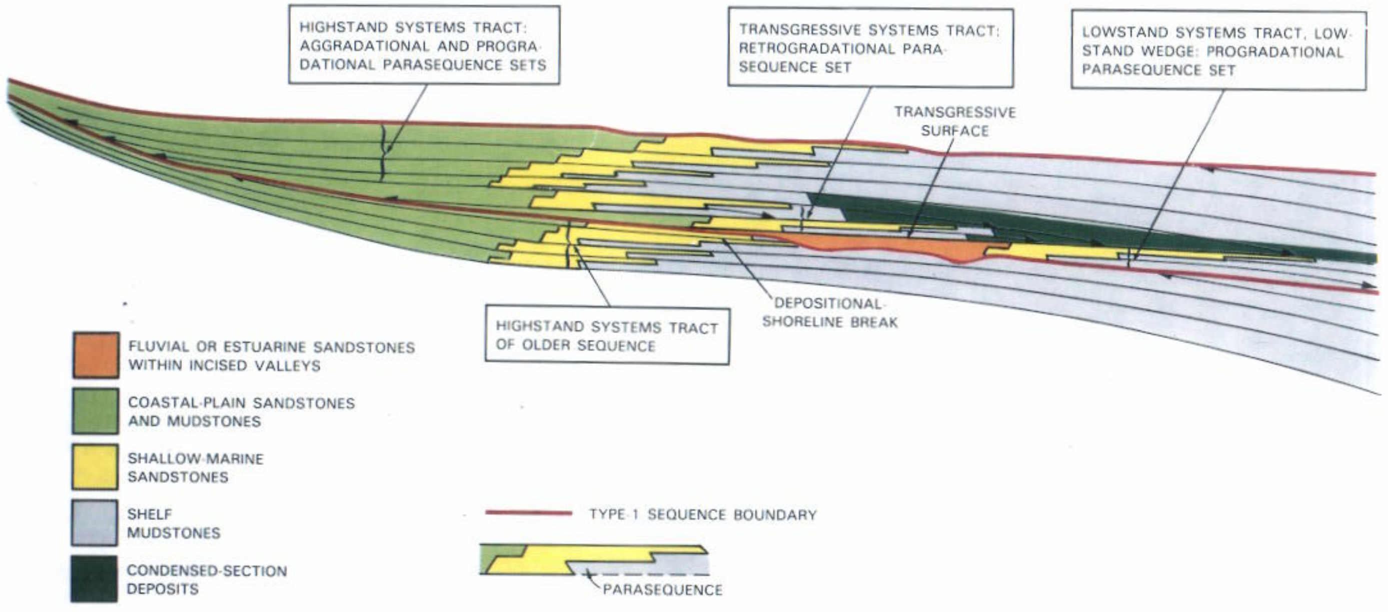

Figure 3. Stratal patterns in a Type-1 sequence deposited in a basin with a ramp margin.

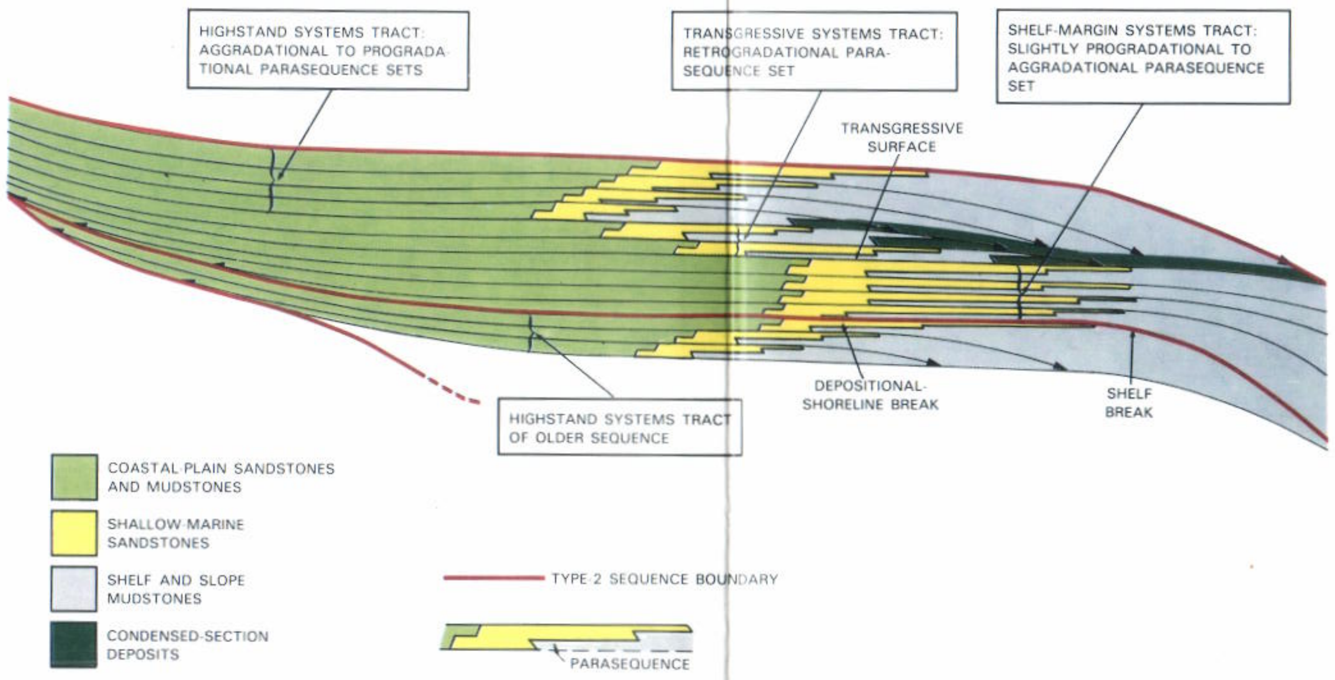

Figure 4. Stratal patterns in a Type-2 sequence.

ATLAS OF SEISMIC STRATIGRAPHY
SHELL OIL COMPANY

INTRODUCTION

This "Atlas of Seismic Stratigraphy" is taken from a 1979 Shell Oil Company publication that was designed and produced for use in Shell Oil Company's Exploration Training program. Its purpose was and still is to demonstrate a basic geologic/geophysical approach to the study of stratigraphy as interpreted from seismic data. Depositional sequences and lithologies are defined by geometric analysis of seismic reflectors complemented by well and outcrop data, although the outcrop data of the original text (except for illustrations of unconformities) are not included in this volume. This atlas expands upon and illustrates many of the concepts presented in AAPG Memoir 26. Since the Shell atlas originally was not planned for publication or public distribution, conventional references or comments, such as "modified from" are not shown. Citations listed in the bibliography recognize the key published work, but not the unpublished Shell work.

ACKNOWLEDGMENT

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COVERAGE

The atlas presented here consists of three parts:

1. Geometric Analysis of Depositional Sequences
2. Facies Analysis of Depositional Sequences
3. Basin Fill Analysis

In a general sense, this order of presentation reflects the steps involved in a typical seismic stratigraphic investigation. Depositional sequences are identified on the basis of reflection terminations. These are calibrated with well data, including age and lithologic information. Where possible, outcrop data may be projected into the line of section. Once the depositional sequences are identified, seismic facies may be interpreted on the basis of internal configuration types and seismic reflection characteristics, i.e., frequency, amplitude, and continuity. These facies should, if possible, be calibrated to lithology and depositional facies interpretations derived from well data. The chronostratigraphic significance of depositional sequences may be tested by constructing a time-stratigraphic chart. A complete seismic stratigraphic analysis requires mapping depositional sequences and seismic facies in three dimensions. From these maps, paleo-environmental interpretations and lithology predictions may be made.

GEOMETRIC ANALYSIS

The first section defines depositional sequences and illustrates various types of bounding unconformities exposed at the surface, in subsurface data, and on seismic profiles. Depositional sequences and the relationship of strata to sequence boundaries are shown on seismic profiles and on well log sections. Seismic well log data are integrated to interpret a series of depositional sequences.

FACIES ANALYSIS

Once sequences are defined, environment and lithofacies within each sequence are interpreted through seismic facies analysis. Internal reflection configurations within a seismic sequence are divided into Parallel and Clinoform reflection types. The various external reflection configurations of seismic sequences are defined from both two- and three-dimensional analyses of forms. Paleo-environmental and lithofacies implications are interpreted on the basis of external and internal reflection configuration and seismic character.

BASIN FILL ANALYSIS

The third section combines the techniques illustrated in the first two sections and sets forth a generalized procedure for making a regional stratigraphic interpretation and basin fill analysis. Each step of a basin fill analysis is demonstrated using the Taranaki basin as an example. The completed basin analysis includes seismic profiles with depositional sequences, environmental and lithologic interpretations, chronostratigraphic charts of seismic sequences, time-stratigraphic correlation charts with lithofacies, and finally, seismic facies maps and paleogeographic maps for each seismic sequence.