Chapter 21

Exploring for Stratigraphic Traps

by

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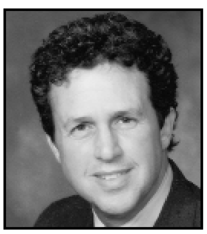

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Overview

Introduction

This chapter reviews methods for locating prospective stratigraphic traps. It stresses the need to use sequence stratigraphy as the framework for data integration. Discussions and examples show how to use sequence stratigraphy to integrate seismic and geologic data. The premise is that effective stratigraphic trap exploration consists of the following steps:

1. Calibrate rocks and fluids to logs and seismic.
2. Apply sequence stratigraphy.
3. Analyze seal, reservoir, and show to find and evaluate traps.

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Section A
Stratigraphic Trap Basics

Introduction

As technology evolves and well control increases, exploration for pure stratigraphic traps becomes more and more practical. Seismic technology produces images of the subsurface with higher and higher resolution. Images and measurements of the subsurface, however detailed, still must be interpreted geologically. Effective geologic interpretation and, therefore, effective stratigraphic trap exploration integrates all data types, including seismic, well log, fluid character, fluid pressure, show, core, and cuttings. Sequence stratigraphy serves as a framework for integrating data.

In this section

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Exploring for Stratigraphic Traps

Introduction

Historically, many stratigraphic traps were found accidentally while drilling for a structural objective. This is due to (1) an historical emphasis on structures and (2) the difficulty in seismically imaging stratigraphic trap components. Most traps are small, due to thin, single-zone pays or short columns created by unfavorable seal geometry or poor-quality seals. Data derived from AAPG memoirs (Halbouty, 1970, 1980, 1982, 1990) suggest that 7.5–12% of the world's giant fields occur in stratigraphic traps.

Definitions

Stratigraphic traps are hydrocarbon accumulations independent of structural or fault closure. **Combination traps** occur where structural nosing and/or faulting modifies the hydrocarbon distribution but is not the sole reason for the accumulation.

Suggested approach

Before sophisticated seismic technology was developed that allowed resolution great enough to image stratigraphic trapping geometry, many (if not most) stratigraphic trap discoveries were accidental. The discoveries were the result of drilling for a structural closure. With the advent of 3-D and other seismic techniques, the exploration industry became more inclined to drill wildcats for stratigraphic traps.

Sequence stratigraphy combines the strengths of seismic stratigraphy with litho- and biostratigraphy to enhance the effectiveness of stratigraphic trap exploration. An effective approach to stratigraphic trap exploration is to apply sequence stratigraphic principles to geophysical and geological data. The table below, modified from Bally (1987), details this approach.

Step	Action
1	*Analyze geometrical relationships in the data.* Break down basin stratigraphy, as displayed in detailed log cross sections and seismic sections, into genetically related sequences using unconformities and other regional correlation features.
2	*Analyze seismic facies and lithofacies.* Identify seismic facies within seismic sequences on the basis of internal and external reflection configurations. Integrate seismic facies with lithofacies interpreted from well data.
3	*Analyze the basin fill.* Make paleogeographic maps of the basin by combining seismic data with paleoenvironmental, chronostratigraphic, and sequence stratigraphic interpretations of lithologic and biostratigraphic data.
4	*Predict the quality and location of reservoir systems and seals.* Identify known and potential reservoir systems and seals.
5	*Evaluate basin for potential traps.* Place known traps in the basin in context with the information gathered in steps 1–4. Use analog traps within the basin and from other basins. Look for trapping geometries in areas with potential charge

Importance of Stratigraphic Trap Seals

Seal geometry

Most stratigraphic and combination traps require top, lateral, and bottom seals to retain a hydrocarbon accumulation. The figure below compares typical structural and stratigraphic traps and shows why bottom seals are more important to stratigraphic traps in determining accumulation size.

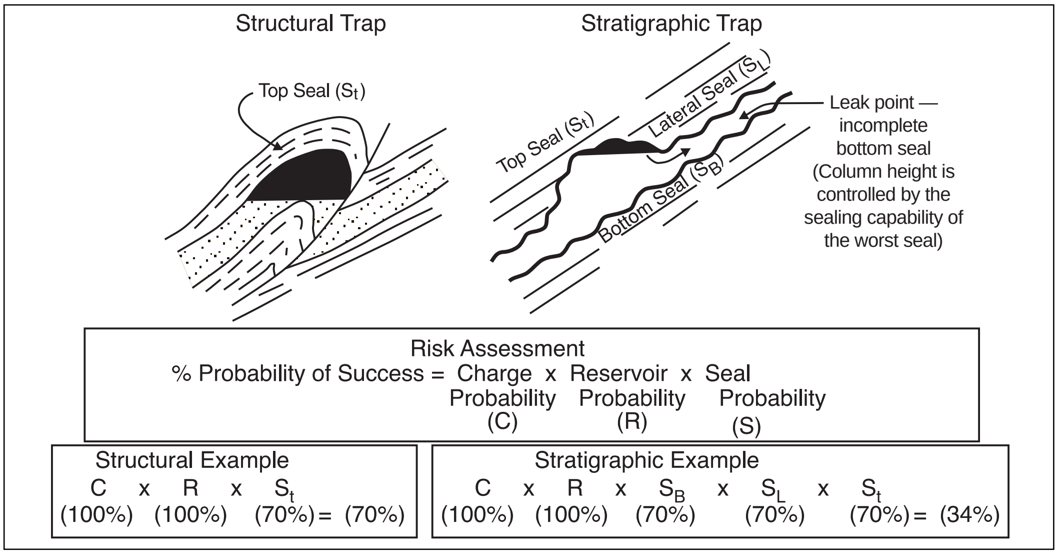

Figure 21–1.

Seal quality and dip rate

Large stratigraphic traps are most common in basins with gentle structural dip, where small hydrocarbon columns can be areally extensive. As structural dip steepens, the need for high-quality seals increases, raising the probability of trap failure (e.g., Gries et al., 1993). That is why large stratigraphic traps are most common in basins with gentle structural dip, where small hydrocarbon columns can be areally extensive. The figure below illustrates in map view how dip rate affects stratigraphic trap size.

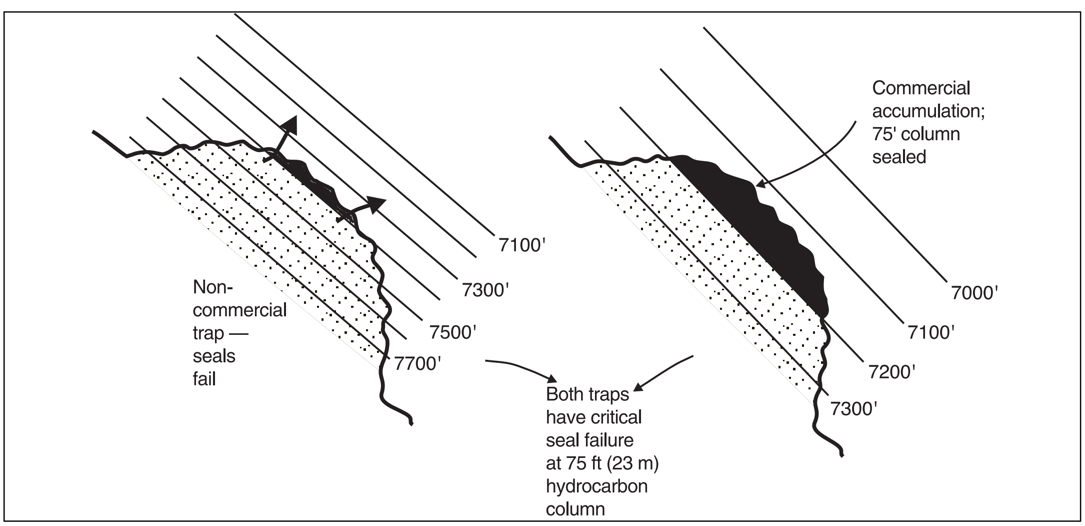

Figure 21–2.

Importance of Stratigraphic Trap Seals, continued

Example

Raven Creek field (with 40 million BOE) illustrates the importance of a bottom seal. It is a paleotopographic trap in the Powder River basin of Wyoming. An unconformity overlying the "A" sandstone of the Permian Minnelusa Formation determines the primary trap geometry. This unconformity has paleotopographic relief, and the Opeche Shale red beds are sabkha deposits that infill an erosional valley forming the top and lateral seals to the "A" sandstone reservoir. The dolostone bed separating reservoir sandstones "A" and "B" provides the bottom seal.

A trap would not form if the valley fill were composed of porous sand or if the bottom-sealing dolostone were absent (from unpublished data by Ralph Thompson, 1986).

The figure below shows a map and cross section of Raven Creek field.

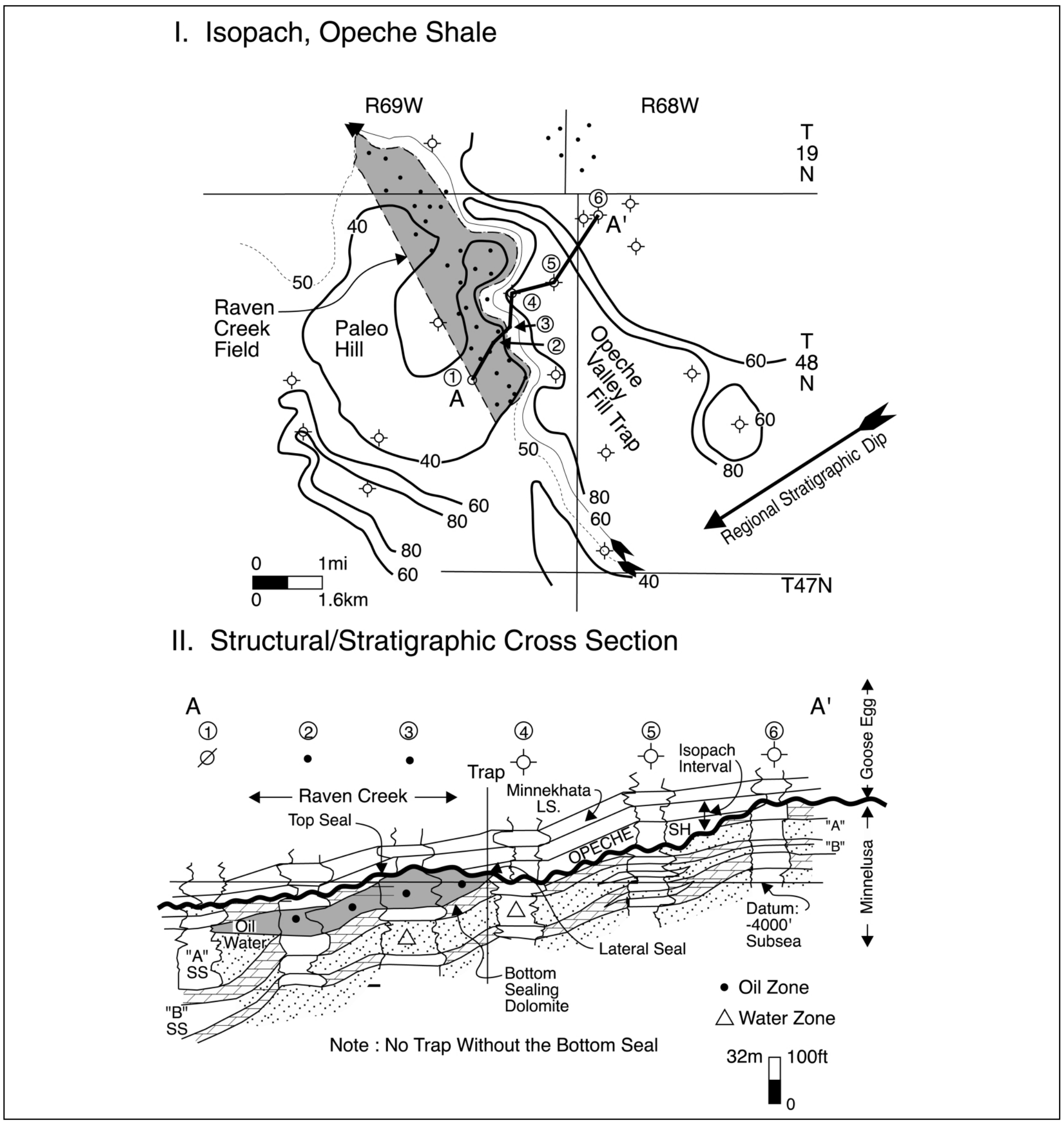

Figure 21–3.

Importance of Stratigraphic Trap Seals, continued

Reservoir quality and column height

Because of leaky seals—especially lateral seals—many stratigraphic traps have short hydrocarbon column heights. In these kinds of plays, reservoir quality can be critical. Higher quality reservoirs require less column height to drive water saturations low enough for water-free production. Lower quality reservoirs require more column height for water-free production.

For example, a trap with 100 ft (32 m) of stratigraphic closure has a maximum column height of 100 ft. If its reservoir is a mesoporous sandstone with 18% porosity and 10 md permeability, then the bottom 75 ft (20 m) of the trap will produce both oil and water in a long transition zone. Commercial production can be reached only at the top, where buoyancy pressure is sufficient to create water-free production.

Importance of Scale

Scale and data type

Correlations with well data, such as cuttings, cores, or well logs, can be done to a much higher resolution than seismic scale correlations. The scale of a seismic wavelet limits the scale of correlations within a seismic section. The geologist must refine these correlations to a higher resolution using well data to more accurately define the location of seals and reservoirs.

Scale and trap detection

Scale makes a difference in ease of detection and, hence, affects risk. In the figures below, Pennsylvanian carbonate reef margin depositional sequences from the Delaware and Paradox basins, U.S.A., are compared. Note the difference in scale and how it affects seismic interpretation. Seismic detection of the Paradox basin traps is much more difficult because of the wavelength of the seismic wave vs. the reservoir thickness.

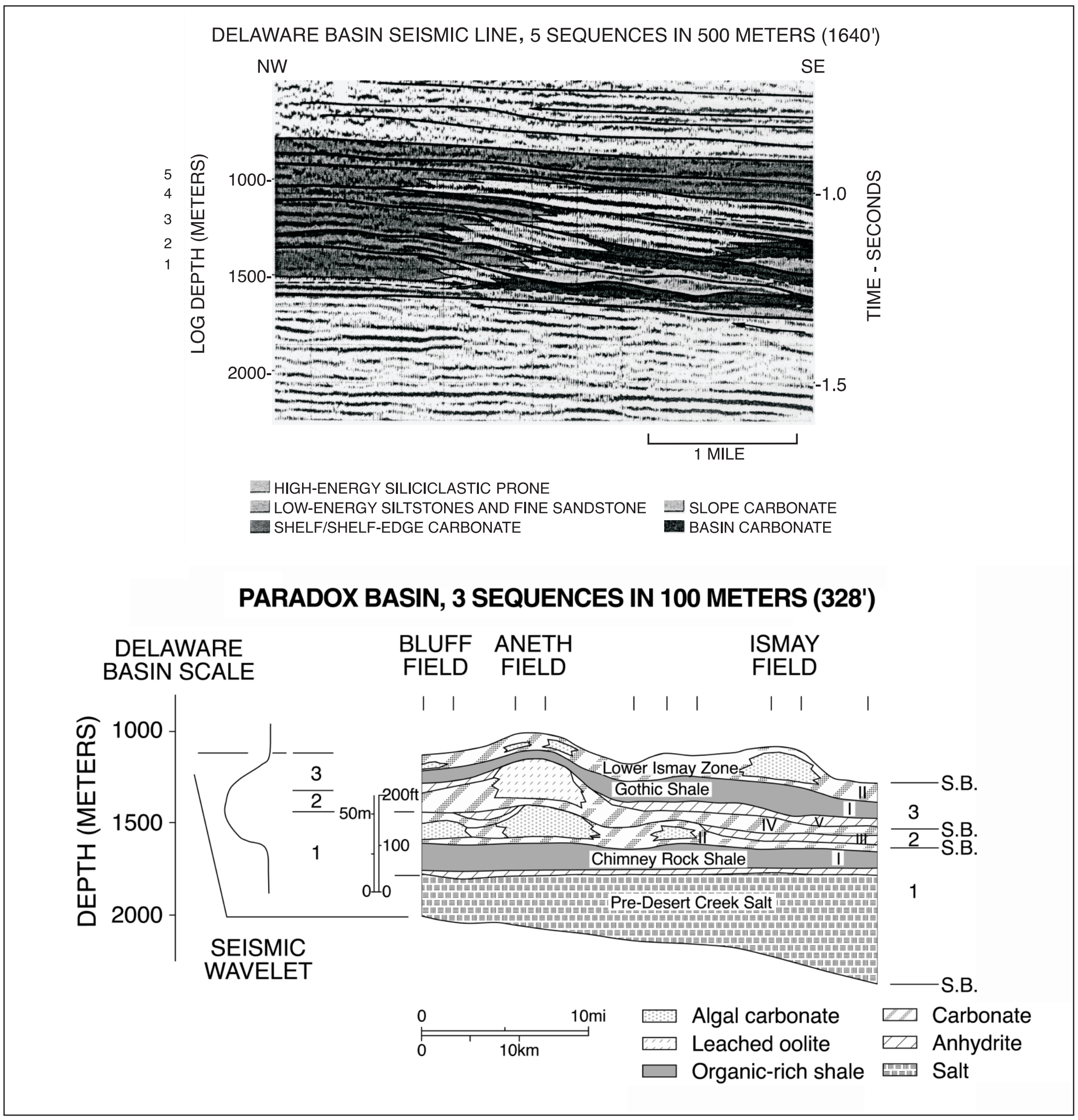

Figure 21–4. From Sarg, 1988; courtesy SEPM.

Impact of Diagenesis

Introduction

Stratigraphic trap geometries can be mapped and defined at any geologic scale from an interpretation of facies in seismic or well data, but diagenetic overprints often modify primary trapping geometries. Diagenetic changes often can be predicted and mapped reliably, especially if they follow facies or paleostructure. However, if diagenesis does not follow facies or paleostructure, then the exploration and exploitation risk increases because predicting the trap location is more difficult.

Example

Access to core, samples, and modern wireline log suites greatly facilitates subsurface interpretation. In the example below, both lateral and top seals in the dolomite reservoir were created by anhydrite cementation during early diagenesis. Primary facies changes do not control the location of the trap.

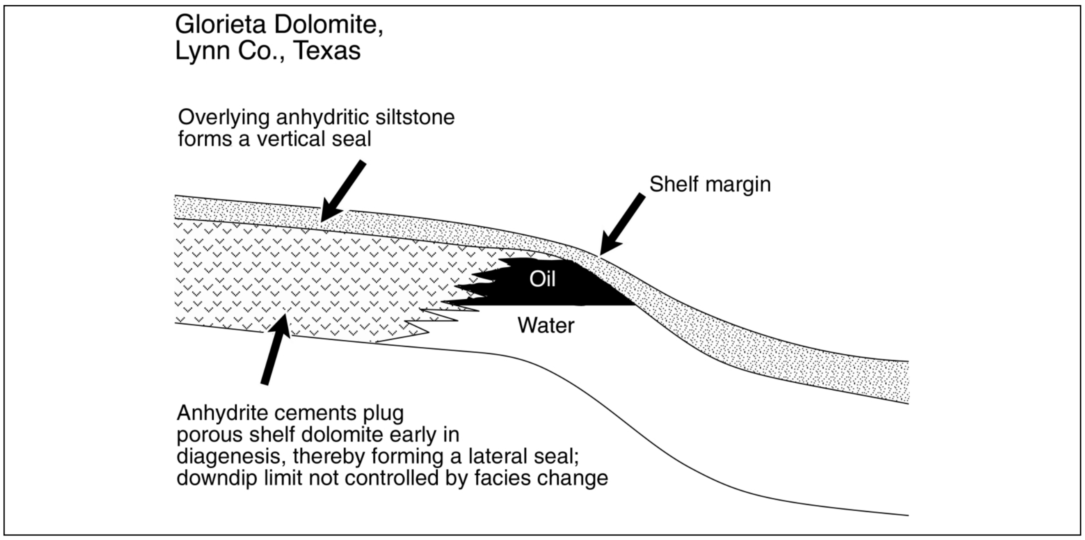

Figure 21–5. From unpublished data by R.C. Tobin, 1987.

Section B

Sequence Stratigraphy

Introduction

Applying the principles of sequence stratigraphy to petroleum exploration leads to more effective prediction of the quality and location of source, reservoir, and seal rocks. This section presents a brief review of sequence stratigraphy. For more detail refer to Wilgus et al., 1988; Van Wagoner et al., 1990; Weimer and Posamentier, 1993; Loucks and Sarg, 1993; and Read et al., 1995.

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Basics of Sequence Stratigraphy

Introduction

Sequence stratigraphy allows an effective, systematic approach to stratigraphic trap exploration. Sequence stratigraphic concepts provide a means to classify, correlate, and map sedimentary rocks using time–stratigraphic units. Sequence stratigraphic techniques provide (1) a more effective method for evaluating reservoir system continuity and trend directions and (2) improved methods for predicting reservoir system, source, and sealing facies away from well control (Van Wagoner et al., 1990). Basic principles are reviewed below, but many important details, model variations, and examples are not included. Interested readers should review the abundant literature regarding sequence stratigraphy (see Weimer and Posamentier, 1993; Loucks and Sarg, 1993; Read et al., 1995; Van Wagoner et al., 1990; Wilgus et al., 1988) and the role of tectonics and rapid sedimentation in stratigraphic architecture (see Dolson et al., 1997; Gawthorpe et al., 1994; Ravnas and Steel, 1998; and Prosser, 1993).

Definition

Van Wagoner et al. (1990) define sequence stratigraphy as "... the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative unconformities." Paleogeographic reconstruction of facies belts at precise moments in time is the goal of the sequence stratigrapher.

Development of sequence stratigraphy

In the late 1970s, seismic data was interpreted stratigraphically to define packages of strata hundreds of meters thick that were deposited between sea level cycles that lasted 0.5–5 m.y. During the 1980s, a finer resolution of stratigraphic analysis developed when outcrop and well data were applied to seismic stratigraphy (Van Wagoner et al., 1990). This type of analysis, termed **sequence stratigraphy**, defines a hierarchy of stratal units that range from thousands of meters to millimeters in thickness and that were deposited by events that range from tens of millions of years to days in duration.

Factors controlling sequence deposition

Four factors control sequence deposition:

- Global sea level changes (eustacy)
- Subsidence
- Sediment supply
- Climate

Other factors that influence sequence deposition (although not to the same extent) are crustal loading, dominant sediment type (i.e., siliciclastic vs. carbonate), basin type, and differential compaction.

Accommodation

Accommodation is the space made available for the accumulation of sediment that results from global sea level change and subsidence. In most cases, subsidence can be considered as constant (Posamentier and Vail, 1988). Accommodation is equal to the rate of eustatic change minus the rate of subsidence. For example, if global sea level is falling at the same rate as subsidence, then no new space is made for sediment accumulation. However, if global sea level is falling but more slowly than the basin is subsiding, then new space is created.

Accommodation (continued)

The figure below shows how, at a point on a shelf, for example, global sea level cycles combine with subsidence to produce accommodation.

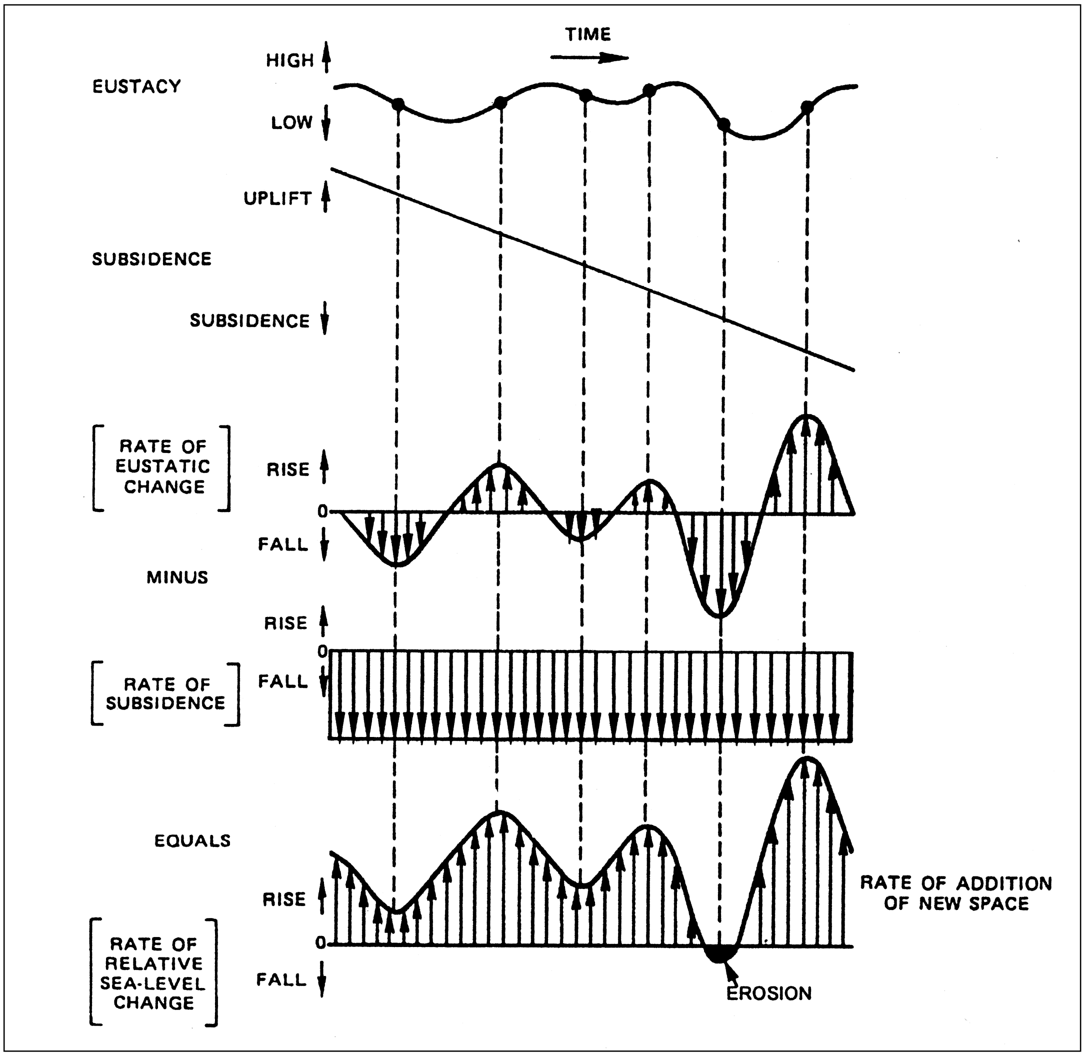


Figure 21–6. From Posamentier and Vail, 1988; courtesy SEPM.

Carbonate vs. siliciclastic deposition

Sediment supply is a greater factor in siliciclastic sequence deposition than carbonate sequence deposition because siliciclastic sediments originate from outside the basin, whereas carbonate sediments originate within the basin. Streams and rivers draining areas landward and updip from the basin deliver sediment to the basin. Organic and inorganic processes produce carbonate sediment within the basin. This plus the unique ability of carbonate sedimentation to keep pace with sea level rise is responsible for the diverse morphology of carbonate platforms, i.e., ramps, rimmed platforms, and isolated platforms. The slope angle of siliciclastic margins is generally less than carbonate margins (Handford and Loucks, 1993).

Hierarchy of Sequences

Introduction

Global sea level changes (eustacy) are cyclic phenomena. Six orders of sea level cycles are recognized from stratigraphic evidence (Van Wagoner et al., 1990). Third-, fourth-, and fifth-order sea level cycles model sequence deposition for petroleum exploration. A third-order sequence is a composite of fourth- and fifth-order sequences.

The table below shows sea level cycle frequencies, thickness ranges, and stratigraphic names for third-, fourth-, and fifth-order sequences.

Sequence Order	Cycle Frequency, m.y.	Thickness, m	Stratigraphic Name
Third	0.5–5	100–1000	Sequence
Fourth	0.1–0.5	1–10	Parasequence
Fifth	0.01–0.1	1–10	Parasequence

Superimposition of cycles

Several frequencies, representing different orders of sea level cycles, are superimposed on one another to make a composite sea level cycle curve. For stratigraphic trap exploration, cycles that impact trap location are usually third-, fourth-, and fifth-order sea level cycles. The figure below shows how adding third-, fourth-, and fifth-order cycles together will produce a composite curve.

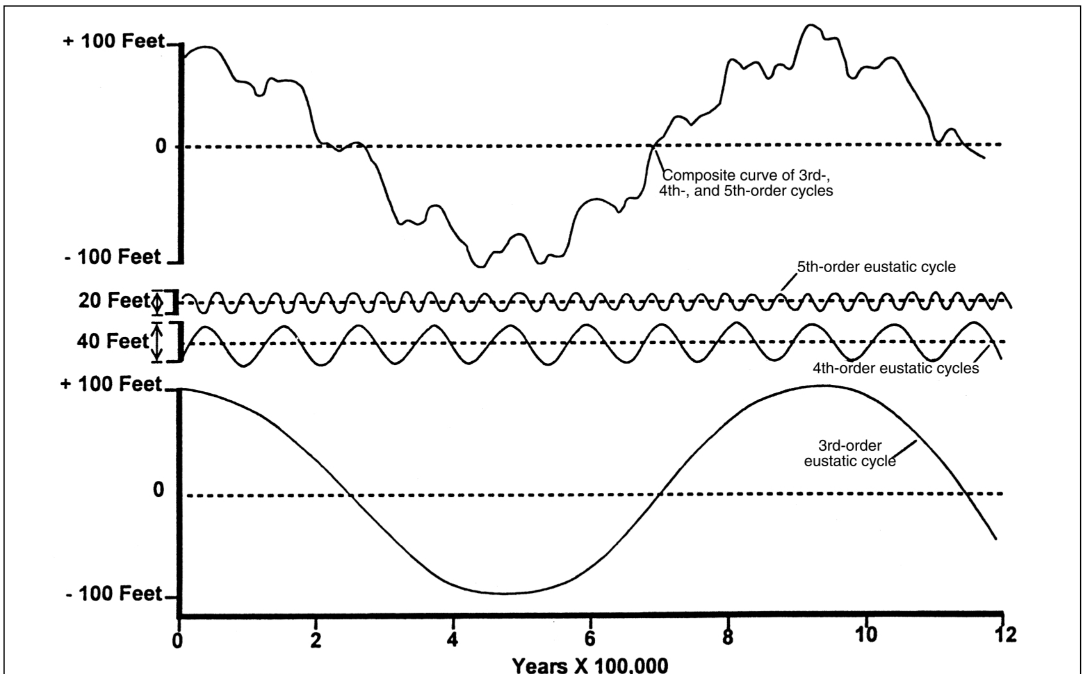


Figure 21–7. From Van Wagoner et al., 1990; courtesy AAPG.

Third-Order Sequences

Introduction

During a third-order sea level change, cycle amplitude is great enough (approximately 50–150 ft) to expose the shelf. Depositional sites range from coastal plain to deep basin. The unit of strata deposited during a third-order cycle is called a **depositional sequence**. A depositional sequence has three subdivisions: highstand systems tract (HST), transgressive systems tract (TST), and lowstand systems tract (LST). The figure below shows a schematic cross section of a third-order sequence and its various systems tracts.

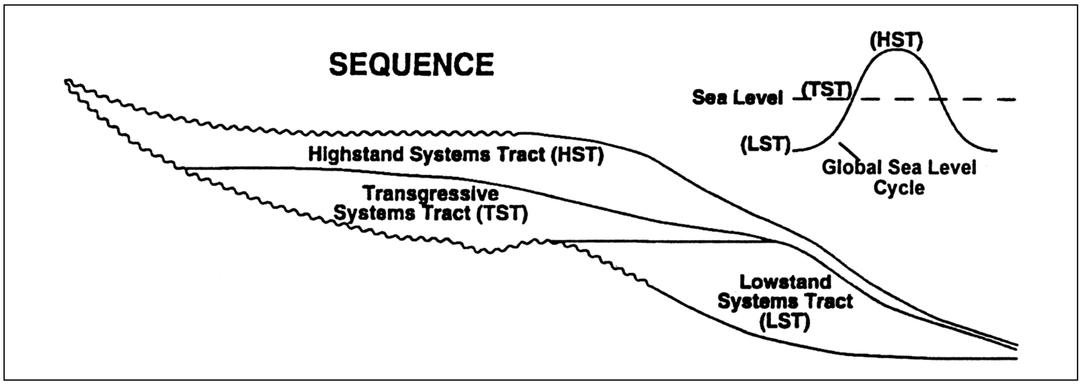


Figure 21–8. From Hyne, 1995; courtesy Tulsa Geological Society.

Third-order sequence deposition

The schematic cross section below is a third-order sequence model based on observations of the Tertiary of the Gulf of Mexico passive margin basin (Van Wagoner, 1990). Although different basin types, i.e., foreland basins or active margin basins, require adjustments to the model, the Gulf of Mexico model still is useful for understanding third-order sequence deposition.

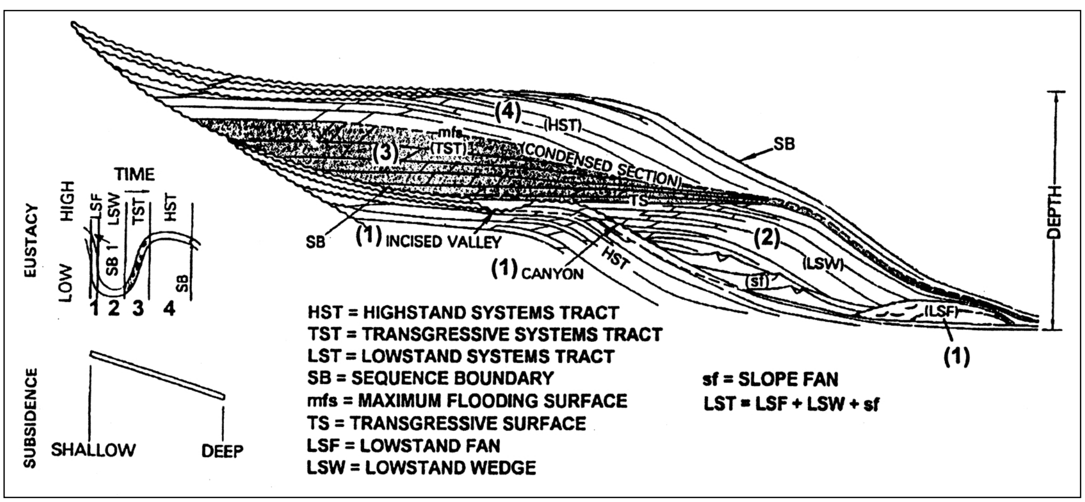


Figure 21–9. From Haq, 1988; courtesy SEPM.

Third-Order Sequences, continued

Third-order sequence deposition (continued)

The order of deposition for the sequence shown in Figure 21–9 is as follows (Van Wagoner, 1990):

1. Sequence boundary formation and lowstand systems tract; fan deposition
   - Rate of eustatic fall exceeds rate of subsidence.
   - Sea level falls to shelf break, shelf is exposed, incised; canyon cut.
   - Slope-perched deltas and submarine fans are deposited.
2. Lowstand systems tract; wedge deposition
   - Rate of eustatic fall decreases, reaches a stillstand, and rises slowly.
   - Submarine fan deposition ceases.
   - Incised valleys fill with coarse-grained, low-sinuosity channel or estuarine sandstones in response to sea level rise.
   - Shale-prone wedge with thin, fine-grained turbidites forms on the slope, then downlaps the top of the submarine fan.
3. Transgressive systems tract deposition
   - Rate of rise is at a maximum.
   - During brief slowdowns in the rate of rise, parasequences (fourth-order sequences) prograde; but overall they stack in a backstepping pattern.
   - Organic-rich (condensed) section moves up onto the shelf.
   - Fluvial systems typically shift from braided to meandering pattern.
4. Highstand systems tract deposition
   - Rate of sea level rise is at a minimum; in the late highstand, it falls slowly.
   - Depositional rates exceed rate of sea level rise, causing parasequences to build basinward in aggradational to progradational parasequence sets.
   - Parasequences downlap onto the condensed section.

Third-order sequence example

The Desmoinian of the Paradox basin, Utah, shown in the figure below, is an example of a third-order depositional sequence.

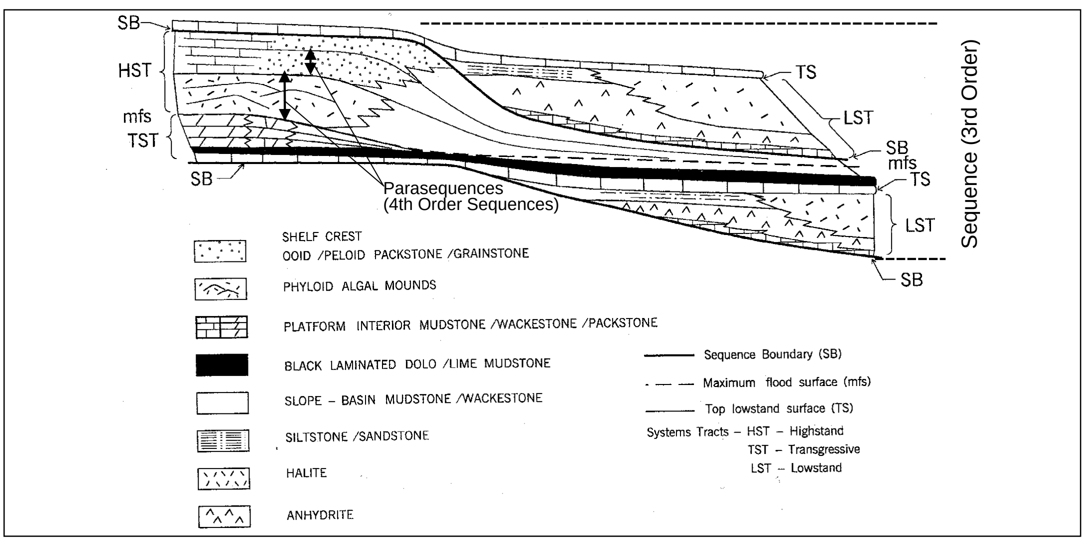


Figure 21–10. From Weber et al., 1995; courtesy SEPM.

Third-Order Sequences, continued

Carbonate platform third-order sequence

The diagrams below outline the deposition of a sequence associated with a carbonate platform during a third-order sea level cycle. Sequence deposition begins with lowstand systems tract (2 and 3) and ends with the highstand systems tract (5).

1. **Highstand**
- Rimmed shelf with accretionary slope apron pattern of progradation

2. **Forced regression**
- Rate of eustatic fall exceeds rate of subsidence
- Sea level is at its lowest point and the greatest area of the platform is exposed.
- Platform eroded and sequence boundary develops
- Submarine fans and megabreccias deposited: beginning of lowstand systems tract deposition

3. **Lowstand**
- Rate of eustatic fall decreases, reaches stillstand, and rises slowly
- Lowstand wedge progrades seaward

4. **Maximum flooding**
- Most of shelf drowns as sedimentation outpaced by relative sea level rise
- Maximum flooding surface forms
- Condensed section develops across shelf, transgressive systems tract deposited
- Shelf margin is scalloped due to frequent collapse.

5. **Highstand**
- Normal shelf sedimentation resumes as rate of relative sea level rise decreases
- Rates of deposition exceed rates of sea level rise: highstand systems tract progrades basinward.
- Facies on shelf reflect inherited topography form the lowstand (e.g., karst) and transgression (e.g., build-ups)
- Shallow shelf-sediments bypass slope to basin floor, which aggrades

Figure 21–11. From Hunt and Tucker, 1993; courtesy AAPG.

Fourth- and Fifth-Order Sequences (Parasequences)

Introduction

Parasequences are deposited during fourth- or fifth-order eustatic cycles. They are generally progradational and have a shoaling-upward association of facies (Van Wagoner et al., 1990). In siliciclastic parasequences, grain size can either fine or coarsen upward, reflecting an upward decrease in water depth. Some workers (Van Wagoner, 1995) consider fourth-order sequences (deposited during cycles 100,000–200,000 years in duration) to be the building blocks of most reservoir or field studies.

Periodic vs. episodic parasequences

A parasequence can be either periodic or episodic (Weber et al., 1995). A **periodic parasequence** has regional continuity and forms in response to deposition during a global sea level cycle. An **episodic parasequence** has limited lateral extent and forms in response to tidal flat migration or delta lobe shifts. Episodic parasequences are of very short duration—generally less than 10,000 years. Periodic parasequences have average durations of 100,000 years.

Parasequence sets

A parasequence set is a succession of genetically related parasequences that forms a distinctive stacking pattern. A parasequence set is generally bounded by a marine flooding surface (Van Wagoner, 1995).

Upward-coarsening parasequence

The figure below shows the characteristics of an upward-coarsening parasequence formed in a deltaic environment.

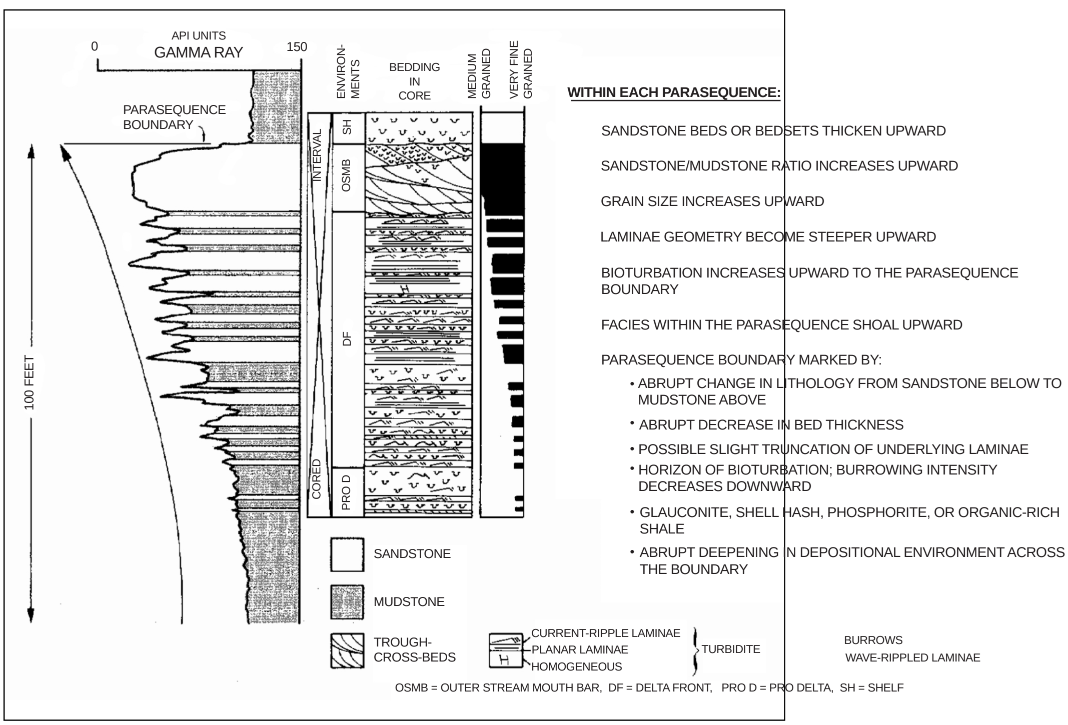


Figure 21–12. From Van Wagoner et al., 1990; courtesy AAPG.

Upward-fining parasequence

The figure below shows the characteristics of two upward-fining parasequences formed in a tidal flat to subtidal environment.

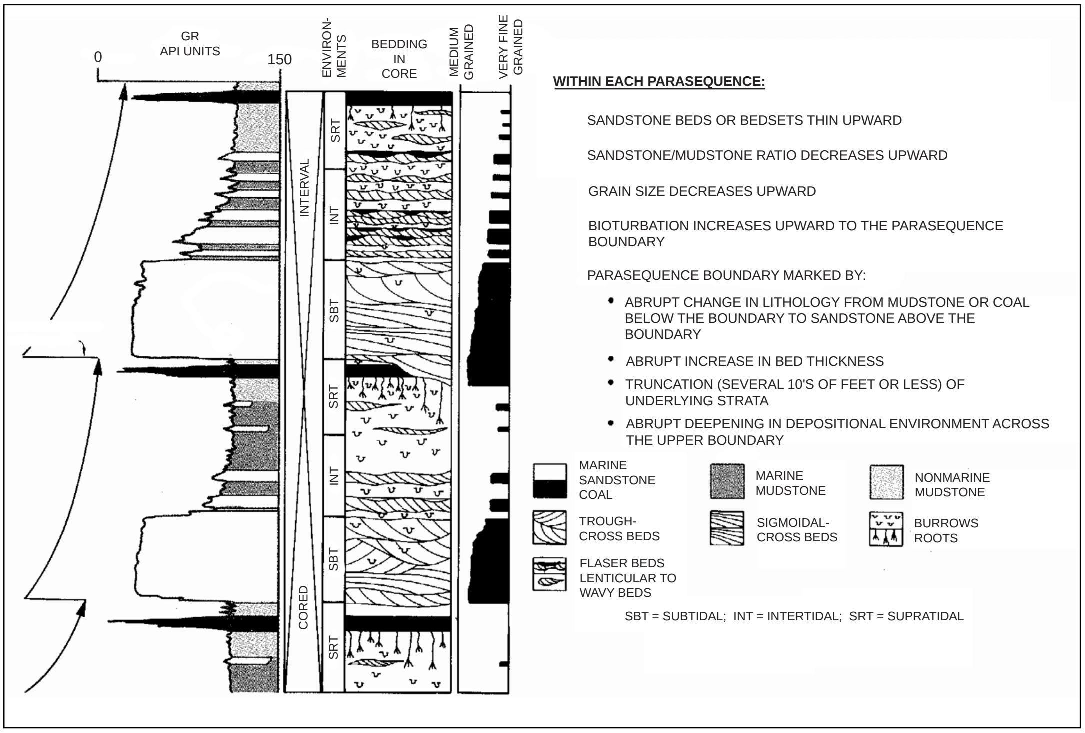


Figure 21–13. From Van Wagoner et al., 1990; courtesy AAPG.

Traps in a Framework of Sequence Stratigraphy

Play types

The schematic cross section below illustrates different stratigraphic play types in the context of sequence stratigraphy.

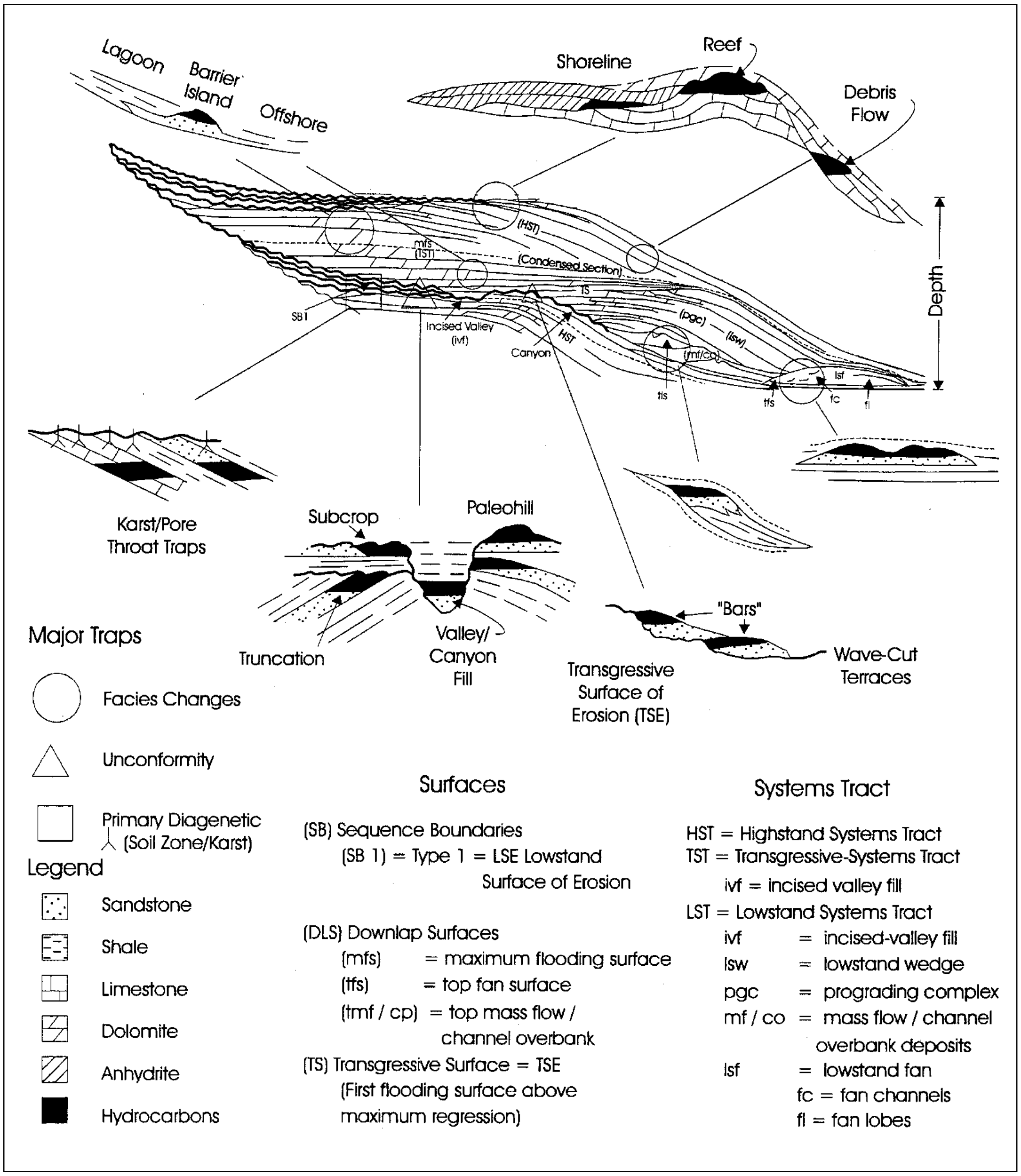
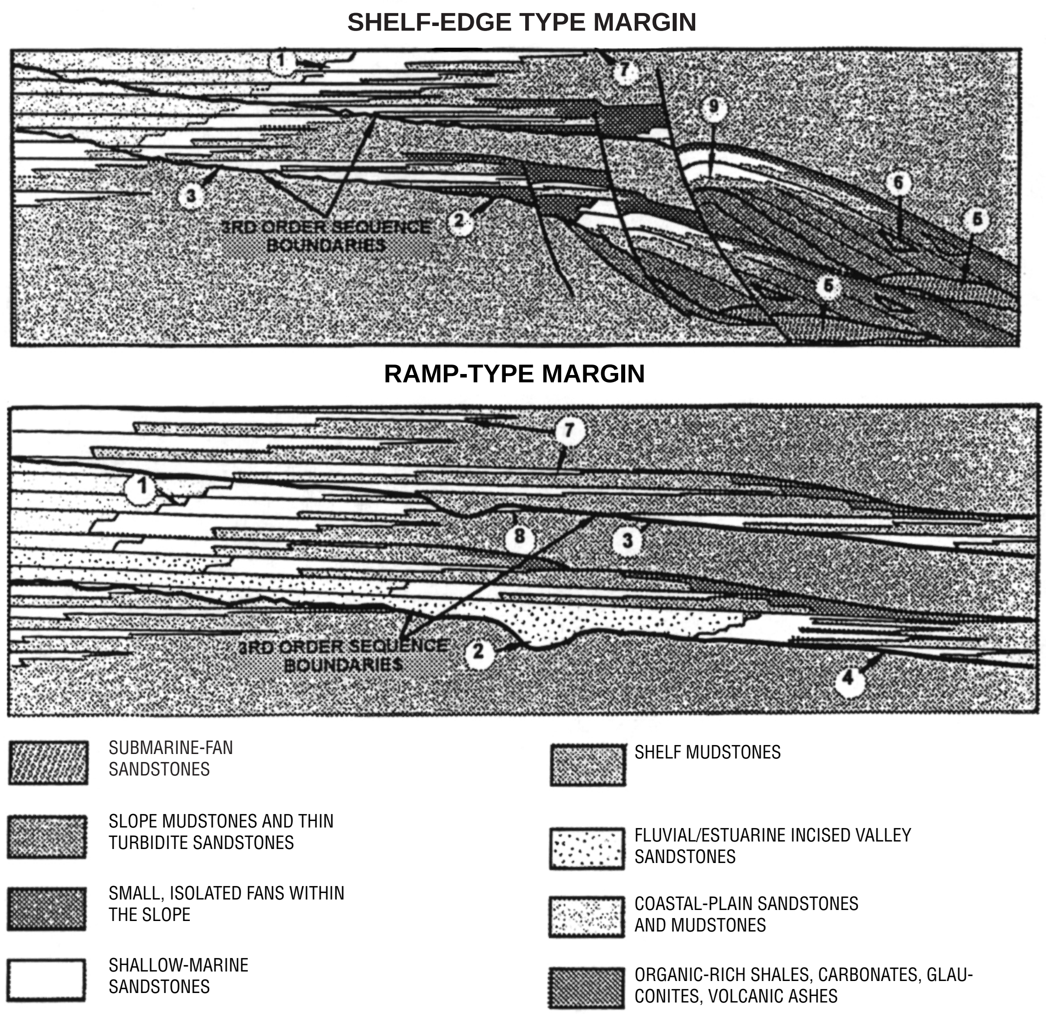


Figure 21–14. Modified from passive margin sequence stratigraphic models by Baum and Vail, 1988, and Sarg, 1988; courtesy SEPM.

Shelf-edge and ramp-type margin traps

Below are two schematic cross sections showing potential stratigraphic and combination stratigraphic–structural plays associated with sequences and parasequences on shelf-edge and ramp margins. Shelf-edge margins are found in continental margin basins. Ramp margins are found in cratonic, continental margin, or lacustrine basins. The numbers in the cross sections correspond to the numbers in the table.



NO.	PLAY TYPE	RESERVOIR
1.	Updip pinchout	Beach or deltaic sandstones
2.	Incised valley	Braided-stream or estuarine sandstones
3.	Shelf onlap	Beach, deltaic, estuarine, or subtidal to tidal-flat sandstones
4.	Basinally restricted onlap	Deltaic sandstones
5.	Submarine fan	Submarine-fan turbidite sandstones
6.	Lowstand wedge	Small, areally restricted fans — composed of thin turbidite sandstones
7.	Downdip pinch-out	Deltaic, beach, or subtidal sandstones (need structural tilt)
8.	Truncation	Beach or deltaic sandstones

Figure 21–15. After Van Wagoner et al., 1990; courtesy AAPG.

Section C
Geometrical Analysis

Introduction

The first step in stratigraphic trap exploration is a geometrical analysis of stratigraphic components of the basin fill. A geometrical analysis consists of (1) dividing the stratigraphic section into depositional sequences, systems tracts, and parasequences and (2) mapping their thicknesses. Correlation surfaces that are genetically significant, such as unconformities, divide the stratigraphic section.

This section discusses procedures and gives examples of geometrical analysis.

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Well Log Sequence Analysis	21–29
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Procedure for Geometrical Analysis

Introduction

A geometrical analysis is simply dividing a basin's sedimentary section into three-dimensional bodies of strata using regionally correlative surfaces or features as boundaries. The sequence stratigraphic approach uses unconformities or other genetically significant features to divide the section into depositional sequences, systems tracts, and/or parasequences. Recognizing these correlation features is key to identifying depositional sequences properly.

Procedure

The table below lists steps for a geometrical analysis of the sedimentary section of a basin in seismic sections, outcrop sections, and well log sections.

Step	Action
1	Identify unconformities (third-order sequence boundaries) in seismic sections, outcrop sections, and regional well log sections.
2	Identify other correlation features, such as maximum flooding surfaces, condensed sections, transgressive surfaces.
3	Divide the sedimentary section into depositional sequences, systems tracts, and parasequences using the following: • Seismic sequence analysis • Well data sequence analysis
4	Map the thicknesses of third-order depositional sequences, systems tracts, and important parasequences.

Identifying unconformities

Unconformities are third-order sequence boundaries. They are generally regional onlap surfaces. In *basinal settings,* they are characterized by onlap of allochthonous deposits (i.e., debris flows, slump deposits, turbidites), prograding deltas, carbonate platform deposits, or evaporites. In *shallow-water or nonmarine settings,* they are characterized by onlap of strata deposited in fluvial, deltaic, or nearshore marine or peritidal environments (Weber et al., 1995). We can identify unconformities using stratigraphic evidence and individual well evidence.

Stratigraphic Evidence

- Reflection terminations in seismic sections (onlap, downlap, toplap, or truncation)
- Bed truncation observed in detailed well log cross sections
- Missing biostratigraphic horizons
- Missing facies in a sequence, i.e., abrupt change from fluvial sandstone to marine shale
- Evidence of widespread channeling of platforms or shelves
- Abrupt vertical geochemical changes such as stable isotopes

Individual Well Evidence

- Dipmeter changes
- Gamma-ray log changes in response to increased uranium concentration at exposure surfaces

Procedure for Geometrical Analysis, continued

Identifying unconformities (continued)

- Vertical breaks in thermal maturity profiles (i.e., abrupt vertical change in vitrinite reflection values)
- Changes in lithology as seen in cores that indicate subaerial exposure or nondeposition, as evidenced by the following:
  - — Paleosols and weathered horizons
  - — Hematitic grain coatings or dissolution textures unrelated to burial diagenesis
  - — Clam-bored hardgrounds such as Toredo borings
  - — Thin lag deposits of bone, phosphate, or shell hash
- Fluid inclusion evidence for atmospheric gases (e.g., argon, helium)

Example of unconformity analysis

Cores and samples should be examined for evidence of unconformities. These unconformity surfaces should then be calibrated to logs. Logs can then be used to correlate the surfaces to seismic and to other wells. The figure below (from Dolson and Piombino, 1994) shows an example of calibrating unconformity evidence from cores to logs. The Lower Cretaceous Cutbank Sandstone unconformably overlies the Jurassic Swift Formation. A major lowstand surface of erosion (LSE) is shown at 2957 ft (901 m) and was identified using the following criteria:

- Missing biostratigraphic horizons
- Subaerial (weathered) zone beneath a channel
- Facies omission (abrupt change from marine shale to a fluvial sandstone)

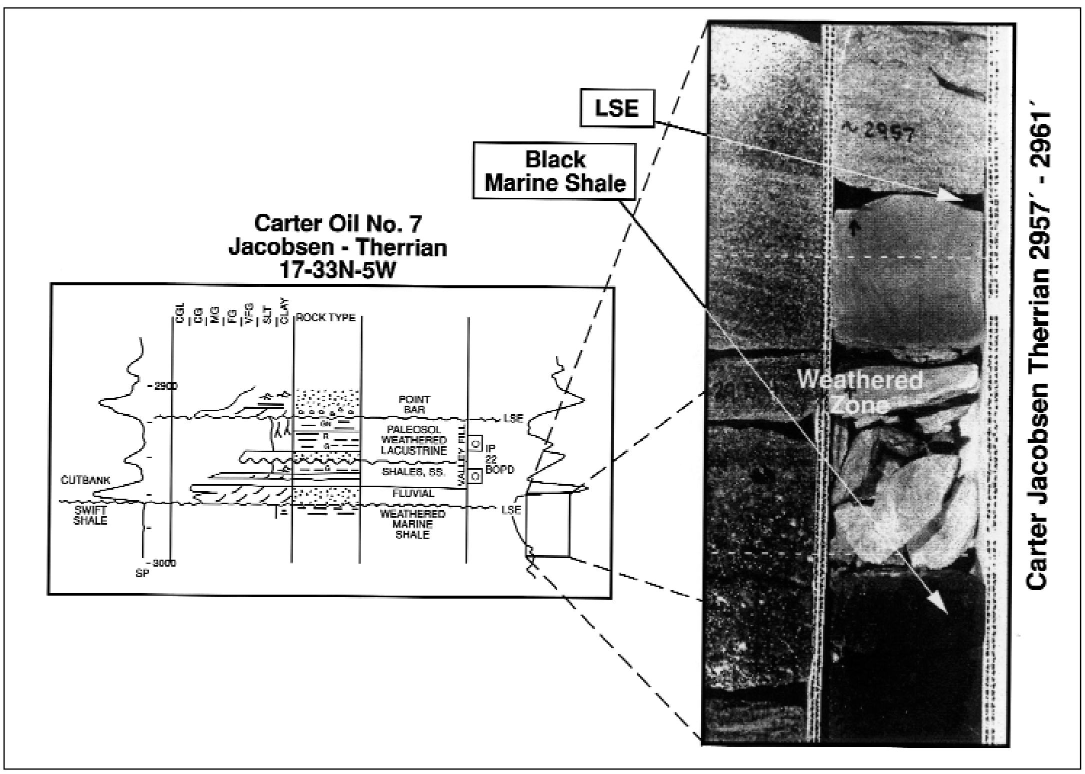

Figure 21–16. From Dolson and Piombino, 1994; courtesy Rocky Mountain Assoc. of Geologists.

Other Correlation Features

Introduction

Besides unconformities, other surfaces and stratigraphic features are useful for correlation. Unconformities serve as boundaries for first-, second-, and third-order sequences. Other correlation features—maximum flooding surfaces, condensed sections, transgressive surfaces, and downlap surfaces—subdivide the third-order sequences into systems tracts and parasequences.

Maximum flooding surface

A maximum flooding surface separates "younger from older strata across which there is an abrupt increase in water depth. This deepening is commonly accompanied by minor submarine erosion or nondeposition, but not by subaerial erosion due to stream rejuvenation or basinward shift in facies" (Van Wagoner, 1995). Submarine erosion ranges from inches to tens of feet, with several feet being common.

A maximum flooding surface represents the point of maximum shoreline transgression. It marks the "turnaround" of the sequence from transgressive to regressive events. The maximum flooding surface is the physical boundary between the transgressive system tract (TST) and the highstand systems tract (HST). In basinward positions, it is contained within the condensed section. In starved areas, it is associated with a hardground or marine dissolution surface (Weber et al., 1995). Galloway (1989) argues that maximum flooding surfaces are more easily recognized and mapped than unconformities and are an alternative method of subdividing sequences.

Condensed section

A condensed section is "a facies consisting of thin hemipelagic or pelagic sediments deposited as the parasequences step landward and as the shelf is starved of terrigenous sediment" (Van Wagoner, 1995). They are most extensive during times of regional shoreline transgressions. Condensed sections contain the greatest abundance and diversity of fauna within a third-order sequence. The section is thin because it accumulates at very slow rates.

Transgressive surface

A transgressive surface forms during a transgression. It is the physical boundary between the lowstand and transgressive systems tracts and is defined by the change from forestepping to backstepping. It merges with the basal unconformity landward of the point where the lowstand systems tract pinches out (Weber et al., 1995).

Downlap surface

A downlap surface (DLS) is a marine flooding surface onto which the toes of prograding clinoforms of the overlying highstand systems tract downlap. The surface represents a change from a retrogradational depositional pattern to an aggradational pattern. It is the surface of maximum flooding, recognized by downlap of overlying units and apparent truncation of underlying units. A downlap surface is common at the base of prograding deltas and the top of submarine fans.

Other Correlation Features, continued

Example: Identifying MFS with biostratigraphic data

In the example below from the Gulf of Suez basin, planktonic and foraminiferal data taken on a 30-ft (9.1-m) interval show abundance peaks crossing a sharp log break from a thin carbonate to marine shale. Abundance peaks such as this are a common feature of the maximum flooding surface (MFS). Seismic and well log correlations confirm that this break is an MFS overlain by a prograding clastic wedge.

The computer-generated labels on the right side post alternative sequence boundary picks. In this way, the interpreter can choose the best pick from all available well and seismic information.

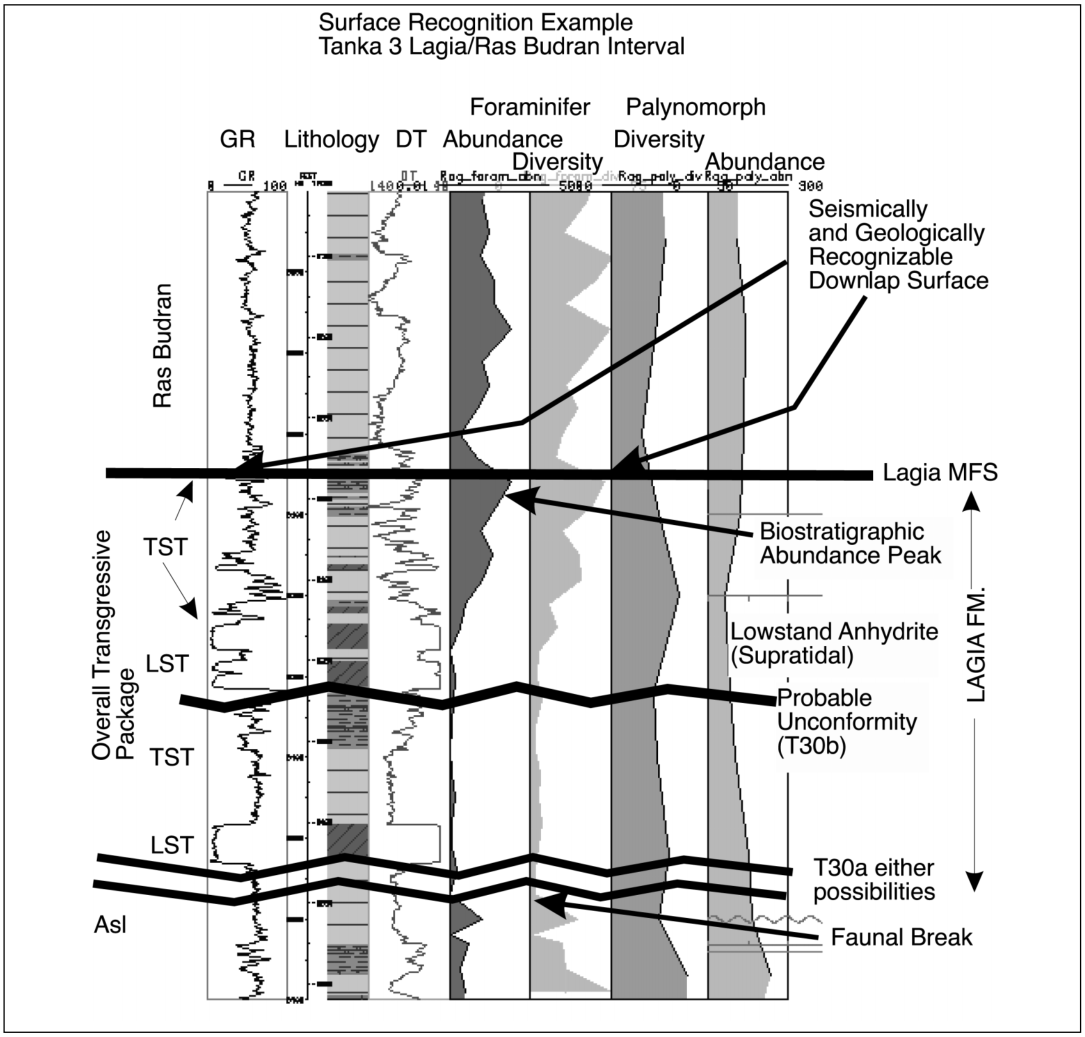

Figure 21–17.

Seismic Sequence Analysis

Objective

The objective of seismic sequence analysis is to identify depositional sequences and systems tracts on seismic sections by interpreting the location of their boundaries. Boundaries are manifested as discontinuities in seismic sections and are located mainly by finding reflection terminations (Vail, 1987).

Procedure

Follow the steps listed in the table below to perform a sequence analysis of a seismic section (adapted from Vail, 1987).

Step	Action
1	Look for places where two reflectors converge. Where reflectors converge, there will be terminations.
2	Mark the reflection terminations with arrows.
3	Draw in the discontinuity surface between the onlapping and downlapping reflections above, and the truncating and toplapping reflectors above. If the discontinuity surface becomes conformable, trace its position across the section by reflection correlation.
4	Continue the process described in steps 1, 2, and 3 for all the seismic lines in the grid.
5	Close all seismic grid loops by checking the loop ties for each discontinuity or its correlative equivalent.
6	Categorize each discontinuity. <table><tr><th>If</th><th>Then...</th></tr><tr><td>It is characterized by regional onlap above and truncation below</td><td>It is probably a sequence boundary</td></tr><tr><td>It is characterized by regional downlap</td><td>It is most likely a downlap surface</td></tr></table>

Marking a seismic section, marking

The table below shows suggested colors for marking seismic sections during sequence analysis (after Vail, 1987).

Feature	Color
Reflection terminations and reflection patterns	Red
Downlap surfaces	Green
Transgressive surfaces	Blue
Sequence boundaries	Miscellaneous

Reflection terminations

The table below groups termination patterns by position with respect to a discontinuity.

Reflection Termination Point	Pattern	Associated Discontinuity
Above a discontinuity	Onlap	Sequence boundary (unconformity)
	Downlap	Downlap surface (condensed section)
Below a discontinuity	Truncation	Sequence boundary
	Toplap	Sequence boundary
	Apparent truncation	Downlap surface

Locating reflection terminations

Locating reflection termination is a matter of finding the patterns described in the table above. The figure below shows these patterns and the associated discontinuity surfaces. HST is highstand systems tract, LST is lowstand systems tract, and TST is transgressive systems tract.

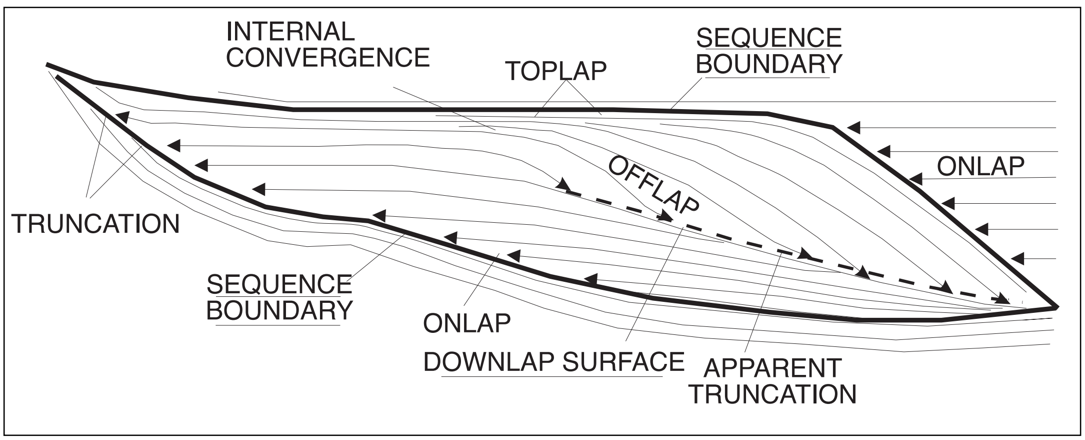

Figure 21–18. From Vail, 1987; courtesy AAPG.

Well Log Sequence Analysis

Introduction

After seismic sections have been analyzed for sequences, well logs are analyzed for sequences and systems tracts. This involves interpreting depositional lithofacies on logs using cuttings and cores and then identifying sequences and systems tracts from the interpreted logs. Stacking patterns displayed in cross sections and individual logs show accommodation space changes which help us identify sequence and systems tracts.

Procedure

The table below, modified from Vail (1987), outlines a suggested procedure for well log sequence analysis.

Step	Action
1	Interpret depositional lithofacies on logs using cores and cuttings to calibrate the log.
2	Estimate sequences and systems tracts from the interpreted lithofacies using regional cross sections with well and outcrop data.
3	Determine accommodation space changes from parasequence stacking patterns seen in well log cross sections (see below).
4	Check estimates of sequences and systems tracts: • Correlate between wells that have biostratigraphic–time correlations, well log marker-bed correlations, and the global sea cycle chart. • Correlate with seismic profiles.

Parasequence stacking patterns

Parasequences stack into three basic patterns as a result of the interaction of accommodation and rate of sediment supply:

- Progradational
- Retrogradational
- Aggradational

Well Log Sequence Analysis, continued

Parasequence stacking patterns (continued)

The diagram below shows these three stacking patterns.

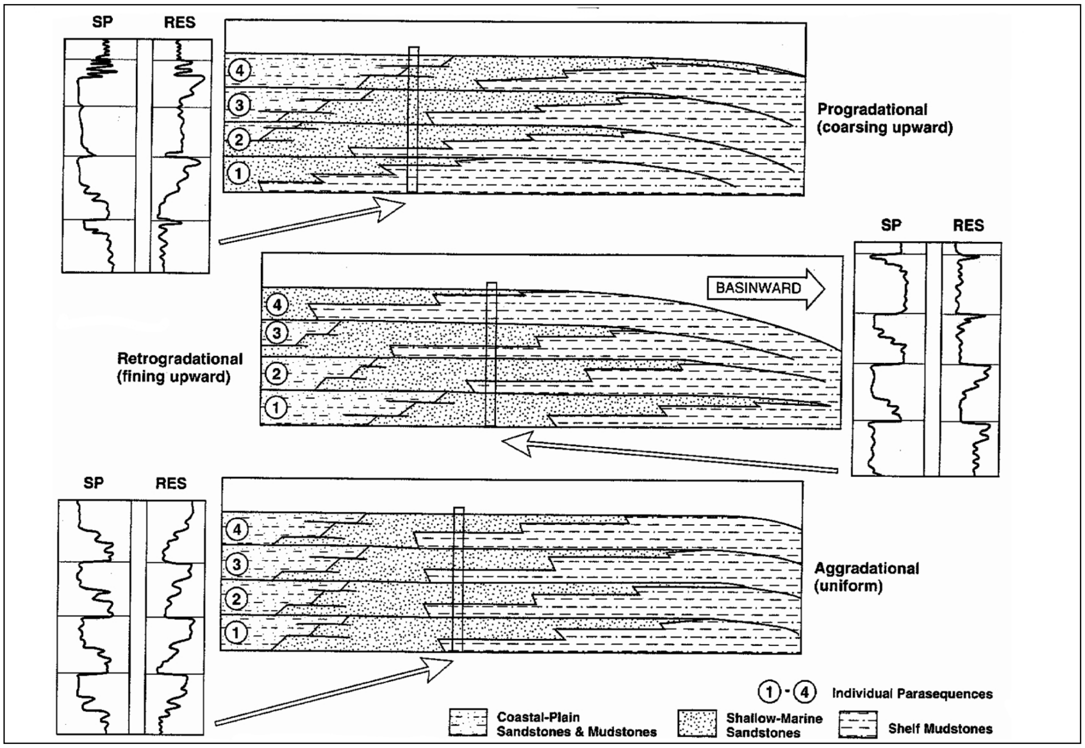

Figure 21–19. From Hyne, 1995; courtesy Tulsa Geological Society. Modified from Van Wagoner et al., 1990; courtesy AAPG.

Stacking patterns for systems tracts

Systems tracts often have characteristic parasequence stacking patterns. Stacking patterns of the basin-floor fan and slope fan, contained within the lowstand systems tract, are difficult to identify. The table below summarizes typical stacking patterns for the three systems tracts.

Systems Tract	Stacking Pattern
Lowstand • Basin-floor fan • Slope fan • Wedge	 Difficult to recognize Difficult to recognize Progradational
Transgressive	Retrogradational
Highstand • Early • Late	 Aggradational Progradational

Well Log Sequence Analysis, continued

Log patterns for systems tracts

The diagram below shows the characteristic parasequence stacking patterns for the high-stand (HST), transgressive (TST), and lowstand (LST) systems tracts of a passive margin basin third-order depositional sequence.

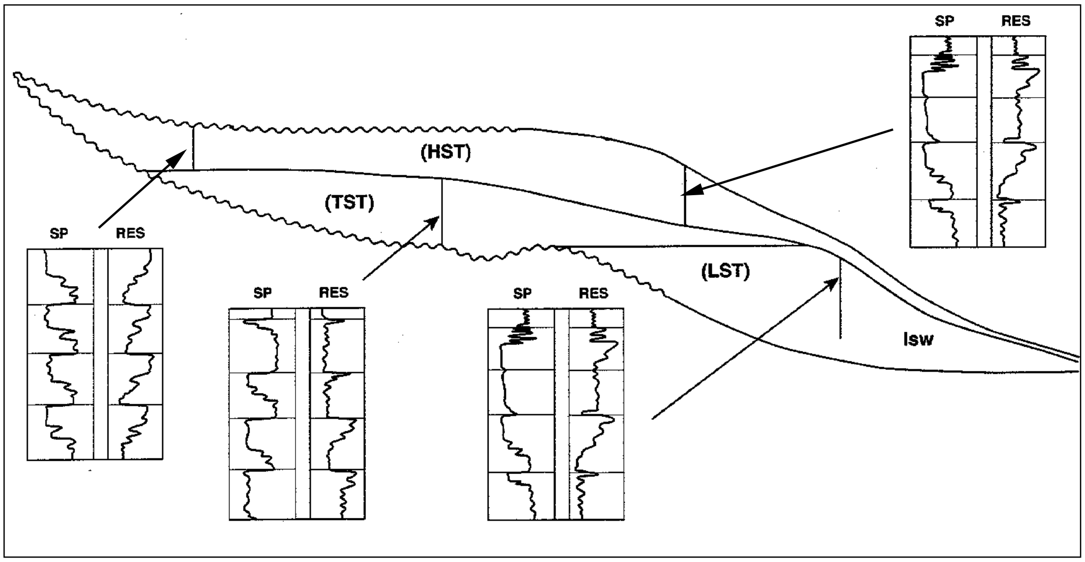

Figure 21–20. Modified from Hyne, 1995; courtesy Tulsa Geological Society.

LST example

The cross section below is from the Late Cenozoic of the Gulf of Mexico. It shows the well log responses of a lowstand systems tract (labeled as PGC, or prograding complex, on the cross section). Log A is completely basinal with a slope fan overlain by shingled turbidites. Logs B and C have deltaic and delta front sands, and midslope turbidite sands. Log D has a "classic" coarsening-upward pattern. Log E has incised valley sands.

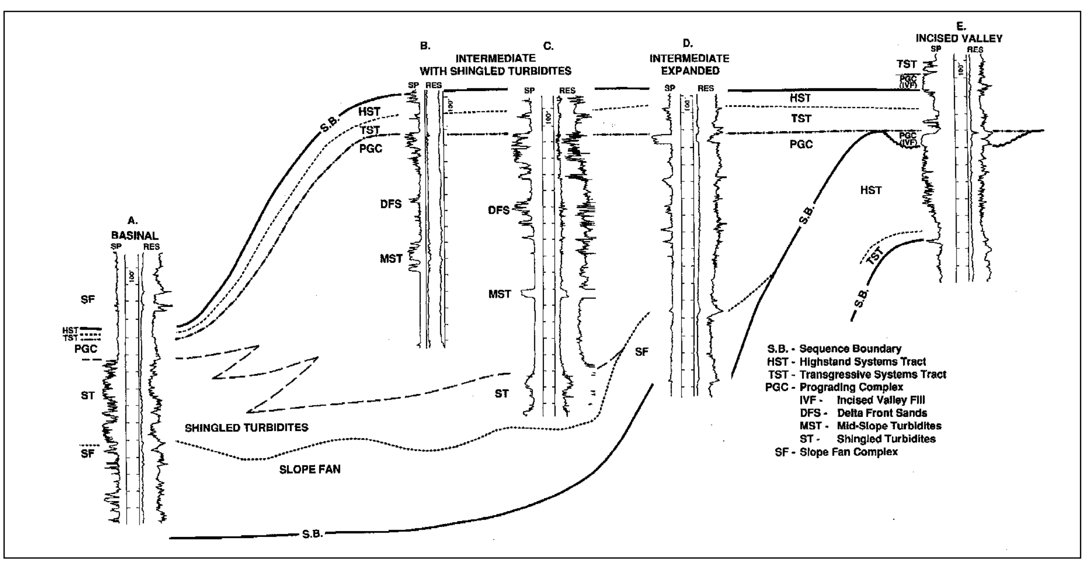

Figure 21–21. From Mitchum et al., 1993; courtesy AAPG.

Combining Well Log with Seismic Sequence Analysis

Introduction

By interpreting depositional sequences in the seismic and well log data separately, discontinuities are identified as objectively as possible on the seismic and log sections before they are tied together using the synthetic seismogram (Vail, 1987).

Objectives

After well logs and seismic sections have been analyzed for sequences, well log and seismic interpretations should be tied together by generating a synthetic seismogram from log information. There are two primary objectives to this step (Vail, 1987):

- To link well log depths to seismic section times.
- To develop an understanding of the causes of constructive and destructive interference patterns of individual wavelets originating from acoustic impedance contrasts.

Using synthetic seismograms

The composite synthetic seismic trace from a synthetic seismogram relates depth information from logs to seismic time. The plots of individual wavelets in a synthetic seismogram show how each impedance interface contributes to the individual reflections. Vail (1987) recommends that seismic sequence analysis and well log sequence analysis be started independently so that boundaries be interpreted as objectively as possible before they are tied together by a synthetic seismogram.

Below is an example of a synthetic seismogram from the Midland basin, Texas.

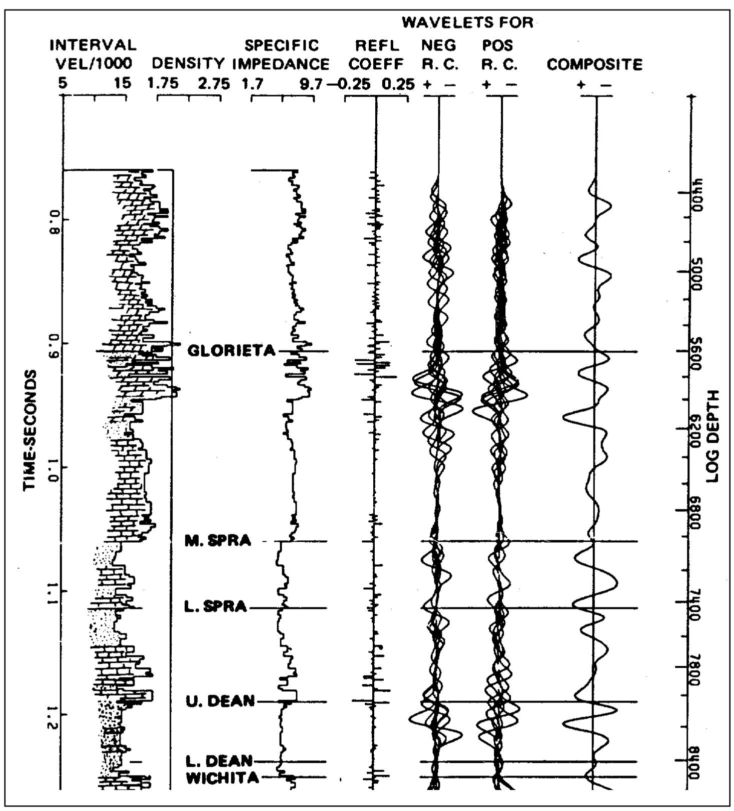

Figure 21–22. After Vail, 1987; courtesy AAPG.

Procedure

Follow this procedure from Vail (1987) to tie well log information to seismic data.

Step	Action
1	Generate a synthetic seismogram from log information (Figure 21–22) using the appropriate software or by asking an expert to create one.
2	Tie well log information to seismic data using the synthetic seismogram.
3	Adjust depositional sequence and systems tract boundaries to the best solution using the ties made in step 2.

Example of integrating synthetics

Synthetic seismograms, or synthetics, can be interactively tied to log, lithologic, and seismic data on geological workstations. The figure below illustrates an example from the Gulf of Suez basin. A wavelet trough forms at a sequence boundary (T55) overlain and sealed by anhydrite and salt. A pronounced wavelet peak forms on an underlying maximum flooding surface. The intervening sequence consists of a lobate deltaic fan formed during a relative highstand. The transgressive systems tract is thin to absent. The geometry of the fan is clear from the well log and seismic integration.

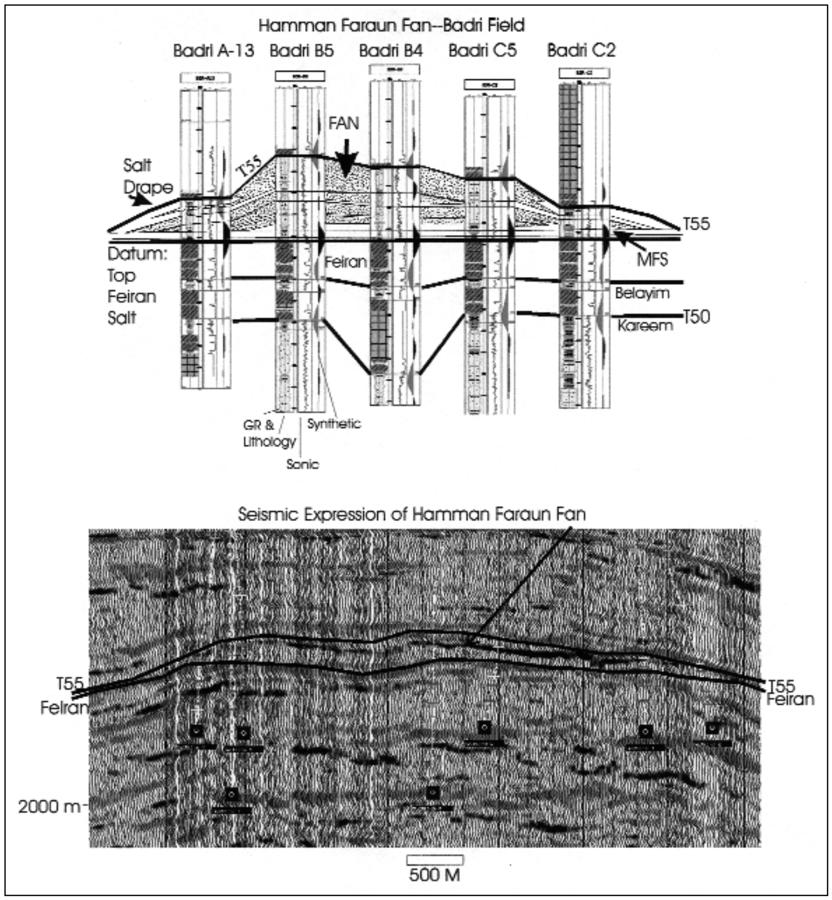

Figure 21–23. From Ramzy et al., 1996; courtesy Egyptian General Petroleum Corp.

Section D
Facies Analysis

Introduction

Seismic facies analysis is the geologic interpretation of seismic parameters as displayed in seismic sequences. Of these parameters, reflection pattern geometries are perhaps the most useful for calibration with lithofacies interpreted from well logs, cores, and cuttings.

In this section

This section contains the following topics.

Topic	Page
Basics of Seismic Facies Analysis	21–35
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Seismic Facies Mapping	21–40
Analyzing Individual Reflectors	21–41
Techniques for Enhancing Seismic Facies Analysis	21–43
Analyzing Lithofacies	21–45
Petrophysical Analysis of Lithofacies	21–46

Basics of Seismic Facies Analysis

Definition and purpose

Seismic facies are mappable, three dimensional seismic units composed of groups of reflections whose parameters differ from those of adjacent facies units" (Mitchum et al., 1977). Seismic facies analysis is the description and interpretation of seismic reflection parameters, such as configuration, continuity, amplitude, and frequency, within the stratigraphic framework of a depositional sequence. Its purpose is to determine all variations of seismic parameters within third-order sequences and their systems tracts in order to determine lateral lithofacies and fluid type changes (Vail, 1987).

Reflection parameters

There are five useful reflection parameters:

- Configuration (reflection geometry)
- Continuity
- Amplitude
- Frequency
- Interval velocity

Depositional environment, sediment source, and lithofacies can be interpreted by grouping these parameters into mappable, three-dimensional seismic facies (Bally, 1987). The table below (after Mitchum et al., 1977) summarizes the information obtained from each parameter.

Reflection Parameter	Geologic Interpretation
Configuration	• Bedding patterns • Depositional properties • Erosion and paleotopography • Fluid contacts
Continuity	• Lateral continuity of strata • Depositional processes
Amplitude	• Velocity–density contrasts of individual interfaces • Bed spacing • Bed thickness
Frequency	• Bed thickness • Fluid content
Interval velocity	• Lithofacies estimations • Porosity estimations • Fluid content

Basics of Seismic Facies Analysis, continued

Seismic facies analysis procedure

The table below outlines a procedure to analyze seismic facies from a grid of sections (vertical) of 2-D or 3-D seismic data (modified from Mitchum and Vail, 1977).

Step	Action
1	Divide each depositional sequence into seismic facies units on all seismic sections.
2	Describe the internal reflection configuration and terminations of each seismic facies unit, i.e., sigmoid, parallel, downlap.
3	Transfer seismic facies descriptions from seismic sections to a shot point map of each sequence.
4	Combine seismic facies distribution and thickness with the map distribution of any other diagnostic parameters, such as interval velocity or localized amplitude anomalies.
5	Integrate well and outcrop data with seismic facies distribution.
6	Interpret the seismic facies maps in terms of depositional settings such as marine or nonmarine, water depth, basin position, energy, transport direction, or any other depositional aspects.
7	Estimate lithology using depositional setting interpretation from step 6 and all available data.

Reflection Configuration Patterns

Groups of configuration patterns

Reflection configuration patterns can be divided into three groups:

- Parallel—including subparallel and divergent
- Discontinuous
- Prograding—caused by lateral accretion of strata

Parallel reflector patterns

Parallel reflections include subparallel, wavy, and divergent. Parallel, subparallel, and wavy reflectors suggest uniform depositional rates on a uniformly subsiding surface, such as a shelf or basin plain. Divergent reflectors suggest lateral variations in depositional rates or progressive tilting of a depositional surface. The figure below shows reflection configurations for this group.

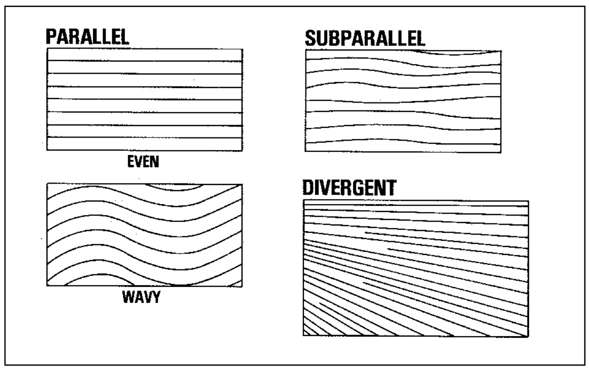


Figure 21–24. From Mitchum et al., 1977; courtesy AAPG.

Discontinuous reflector patterns

Five types of discontinuous reflector patterns that help interdepositional systems are shown in the figure below. Hummocky strata may be discontinuous point bars and crevasse splays. Chaotic reflectors suggest coarse-grained fluvial or turbidite channel fills. Contorted features may be shale-prone debris flows. Precise identification of depositional environments requires integration with other data.

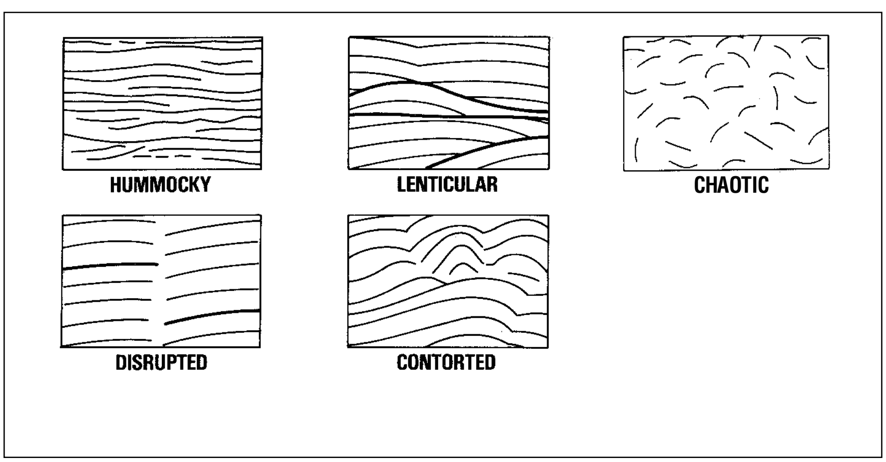


Figure 21–25. After Mitchum et al., 1977; courtesy AAPG.

Reflection Configuration Patterns, continued

Prograding reflector patterns

One of the most common depositional features observed in seismic sections are clinoforms manifested in a configuration pattern called *offlap*. Clinoforms are progradational strata that form through the progressive development of gently sloping surfaces. Paleowater depths can be interpreted from the height of prograding clinoforms. The diagram below shows prograding reflectors and their possible depositional significance.

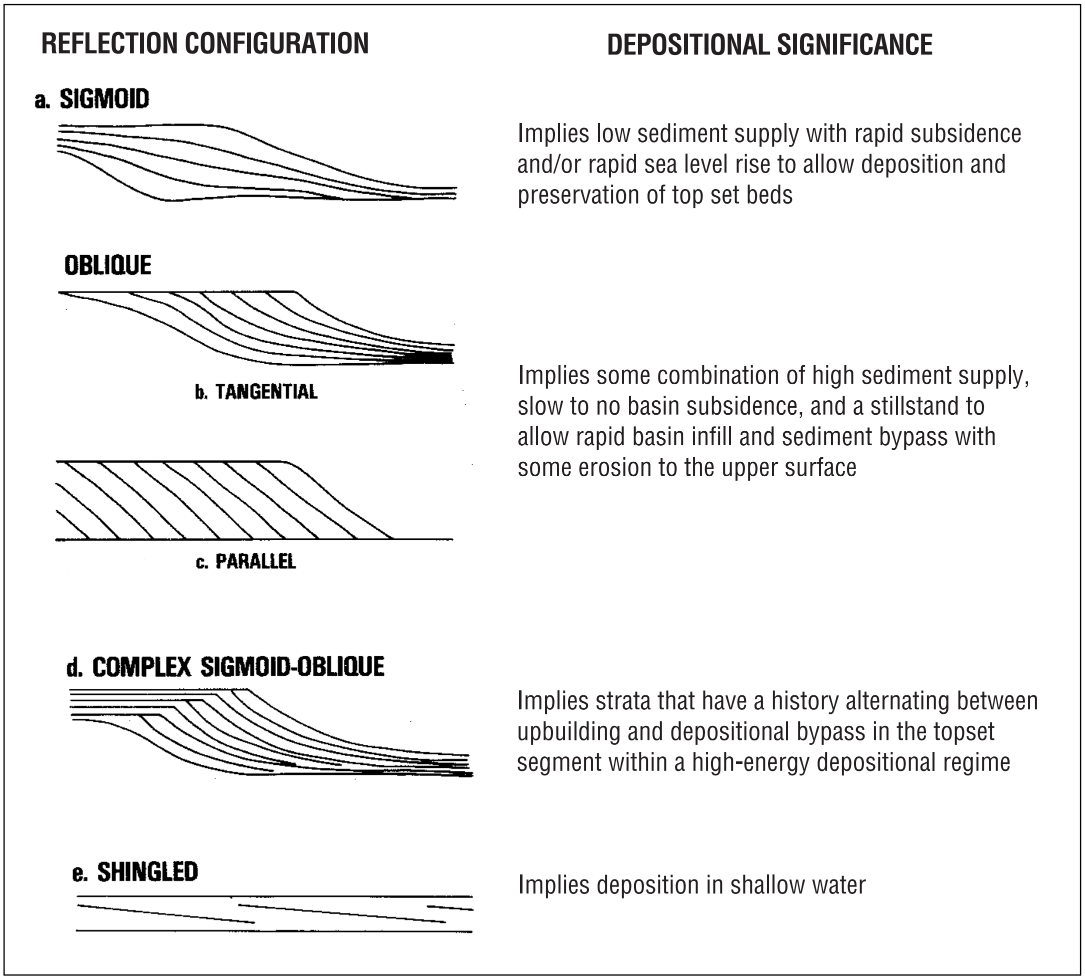


Figure 21–26. After Mitchum et al., 1977; courtesy AAPG.

Reflection Configuration Patterns, continued

Channel fill patterns

Channels are expressed in seismic sections as negative relief features truncating the underlying strata. Fill patterns are shown in the figure below.

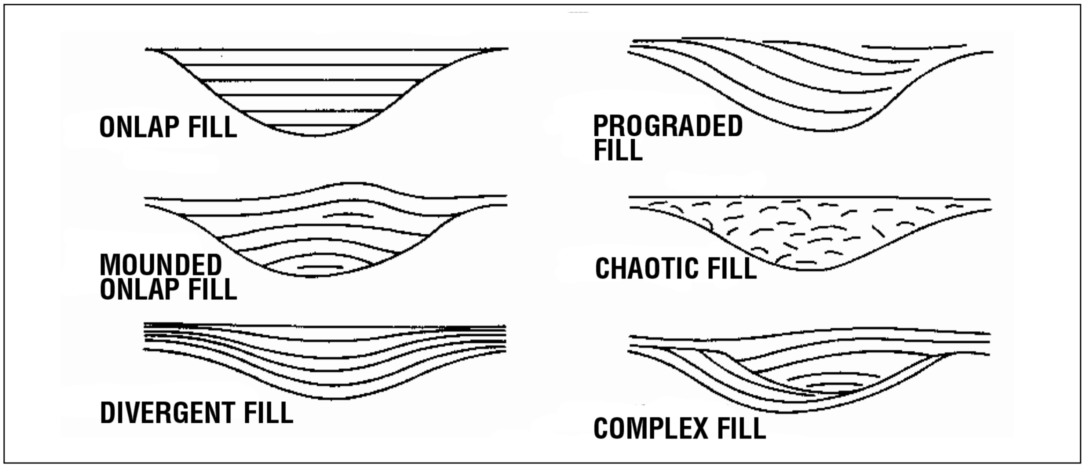


Figure 21–27. From Mitchum et al., 1977; courtesy AAPG.

Seismic Facies Mapping

Introduction

Seismic facies maps show the areal distribution of seismic facies and are useful when making lithofacies interpretations. The most common and useful parameters to be mapped are seismic reflection patterns and isochrons (thickness measured in seconds of two-way time).

Procedure

The table below outlines a suggested procedure for mapping seismic facies.

Step	Action
1	Identify sequences that contain potential traps, seal rocks, reservoir rocks, or source rocks.
2	Make regional seismic reflection pattern maps and isochron maps of those sequences. If possible, make maps of lowstand, transgressive, and highstand systems tracts.

Example

The figure below contains examples of a seismic facies map, an isochron map, and seismic line A–Á (location shown on maps).

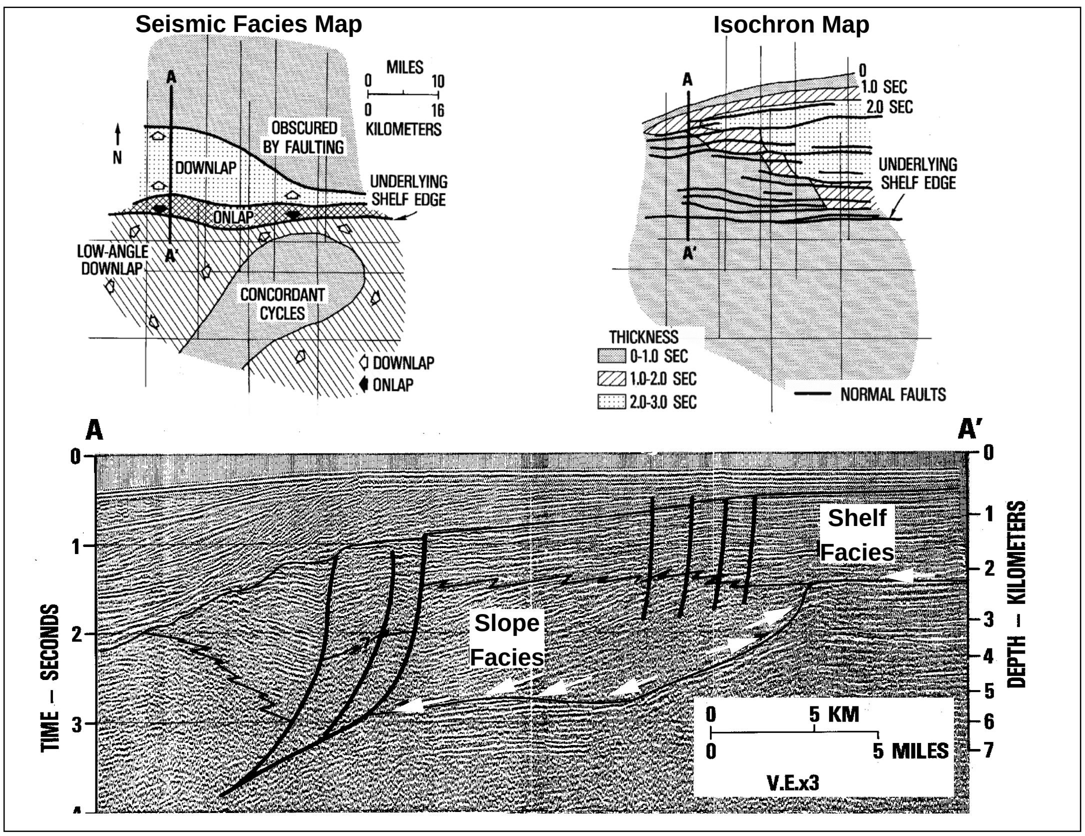


Figure 21–28. Modified from Mitchum and Vail, 1977; courtesy AAPG.

Analyzing Individual Reflectors

Introduction

We can enhance our recognition of stratigraphic features by using seismic data attributes, reflection strength, coherence, and instantaneous phase. These attributes are well suited to stratigraphic interpretation and are an effective interpretive tool when displayed in map view.

Seismic data attributes

Seismic data attributes and their use in seismic facies analysis are listed in the following table.

Attribute	Use
Reflection strength	• Lithologic variation • Facies mapping • Porosity prediction • Thin-bed analysis • Character correlation
Instantaneous phase	• Reflector configuration • Reflector continuity • Reflector terminations
3-D coherence	• Facies mapping • Character correlation • Fault identification • Paleogeomorphology

Reflection strength

Reflection strength is a measure of the total energy of a reflection, manifested in reflection amplitude. It is independent of phase. Reflection strength is also referred to as the instantaneous amplitude, or envelope amplitude. Analysis within specific reflectors can give us clues to changes in lithology or porosity.

Instantaneous phase

Instantaneous phase is an amplitude-independent attribute that highlights reflector continuity. It is useful for enhancing reflector terminations, particularly in areas with weak, low-amplitude events. Reflector terminations appear much clearer, which allows for an easier understanding of the geometry of individual packages of reflectors.

3-D coherence

Three-dimensional coherence is a measure of the similarity of neighboring seismic traces in 3-D data. It is useful for mapping paleogeomorphology and faults (Bahorich et al., 1995).

The map below is a 3-D coherency slice of a Miocene channel complex in the Nile Delta, Egypt.

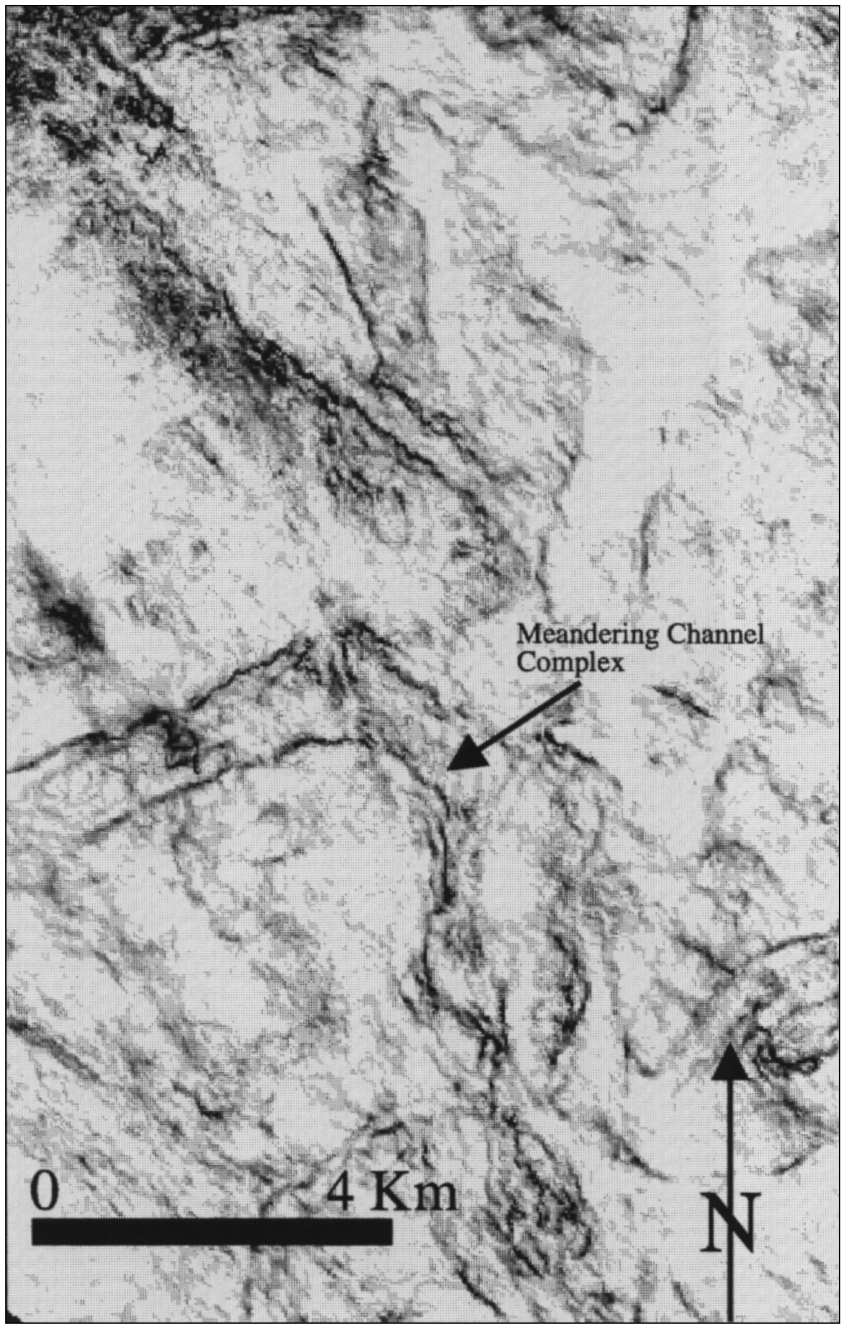


Figure 21–29. From Wescott and Boucher, 1998; courtesy AAPG.

Techniques for Enhancing Seismic Facies Analysis

Introduction

Additional techniques for improving resolution and enhancing interpretations of seismic facies include the following:

- Seismic forward modeling
- Changing display scale for seismic data
- Changing display type for seismic data
- Using 3-D seismic displays

Seismic forward modeling

Forward modeling begins with a model in depth and coverts it to time. Put another way, forward modeling takes a 2-D or 3-D geological model and converts it to a simulated seismic section. The simulated seismic section can be compared to the actual seismic data. The geological model is adjusted until there is a match.

Forward modeling has three purposes (Vail, 1987):

- Interpret stratigraphy and fluid composition at or near the limits of seismic resolution by waveform analysis.
- Simulate a geologic cross section seismically, showing stratal surfaces and impedance contrasts.
- Simulate reflection patterns seen in seismic sections by calculating stratal patterns from rates of subsidence, eustasy, and sediment supply.

Changing display scale

Choice of display scale can be critical in detecting subtle features in seismic data. Minute changes in dip are often difficult to detect on wiggle trace displays plotted at traditional scales. When such displays are horizontally compressed and vertically expanded, stratigraphic changes are magnified accordingly and become more visible. Unfortunately, structural changes are also magnified. This effect can be attenuated by flattening on an interpreted structural horizon.

Changing display type

Choice of display type can also be critical in detecting subtle features in seismic data. Two types that help in seismic facies analysis are horizontally compressed wiggle displays and color amplitude displays. Horizontally compressed wiggle displays also reduce the trace excursion or amplitude of the reflections, making important changes in reflectivity more difficult to discern. Color amplitude displays retain amplitude fidelity regardless of scale and are particularly useful when viewing horizontally compressed, flattened displays. These are often helpful in stratigraphic interpretation of subtle features.

3-D seismic displays

For stratigraphic interpretations, 3-D seismic data has a significant advantage over standard 2-D data because it images the subsurface at a much closer spacing, delineating very subtle changes in reflectors. The ability to map channels, fan lobes, pinch-outs, and other features is greatly enhanced. Amplitude, phase, and frequency can be mapped aerially in considerable detail, resulting in striking visual images of subsurface stratigraphic features. Horizon-based amplitude extractions are one of the most routinely used 3-D seismic display types. Changes in amplitude along a reflector may indicate changes in lithology, porosity, or fluid saturation. For additional details, see Brown (1999).

Example: Compressing vertical scale

Older-vintage 2-D seismic data are often difficult to interpret for subtle stratigraphic changes. The figure below, depicting the northern Powder River basin, Wyoming, shows the impact of compressing seismic sections on a workstation. A 6.4-km, 32-m-deep valley network incised in the Muddy Formation (Lower Cretaceous) is difficult to see on the original data display. However, by compressing the display, the incised valley fill becomes easier to recognize.

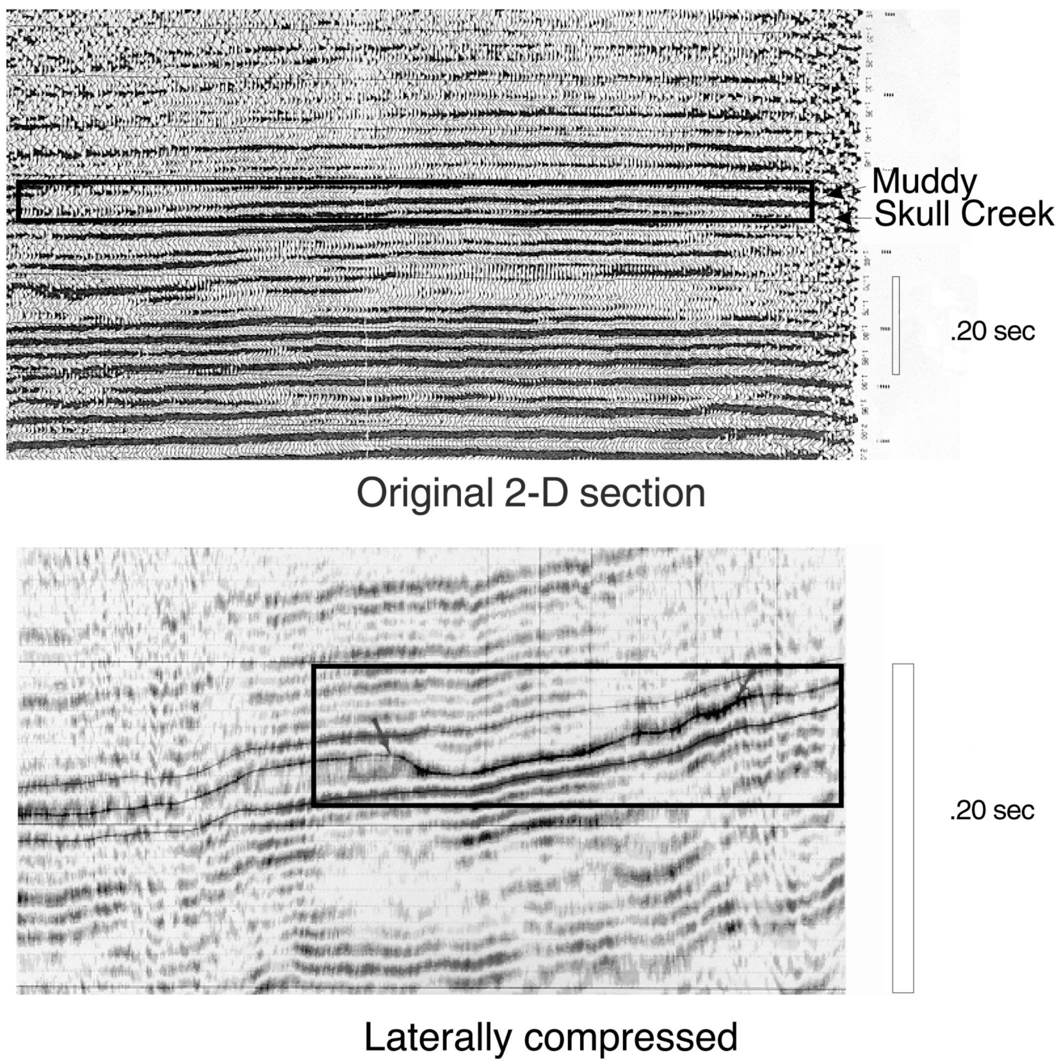


Figure 21–30. Unpublished data courtesy BP-Amoco.

Analyzing Lithofacies

Introduction

Lithofacies are interpreted from well data and seismic facies descriptions. Lithofacies interpretations should be based on all available well and outcrop data and on seismic facies interpretations.

Procedure

Below is a suggested procedure for analyzing lithofacies.

Step	Action
1	Learn as much as possible about the regional geology from well and outcrop control.
2	Describe cores and cuttings from sequences of interest. Besides describing lithology, grain size, and sedimentary structures, also describe pore geometry.
3	Calibrate core and cuttings descriptions to well logs and outcrops. Annotate logs with porosity and permeability data (if available) from potential reservoir and seal intervals.
4	Integrate calibrated well logs into well log cross sections constructed during well log sequence analysis.
5	Interpret depositional environments of lithofacies of depositional sequences using log cross sections and seismic sections with seismic facies analyses.

Petrophysical Analysis of Lithofacies

Introduction

The reservoir or seal quality of a rock is established soon after deposition. It is strongly influenced by its environment of deposition. Diagenesis can alter or completely change the original pore space of a rock, especially for carbonates. However, if the original pore space is not altered too much, then a relationship exists between lithofacies and reservoir- or seal-quality rocks that we can use when prospecting for stratigraphic traps. A petrophysical analysis of the lithofacies of a rock section in a target area can help determine if such a relationship exists.

Procedure

After lithofacies analysis, a careful petrophysical analysis of shows and production should be made and compared to lithofacies distribution. The table below suggests a procedure for petrophysical analysis.

Step	Action
1	Gather all available fluid data regarding production, shows, and pressures from prospective intervals.
2	On structural cross sections, plot intervals that ... • Were perforated • Had DSTs • Had RSTs • Had mud log shows Annotate the intervals with the results.
3	Divide potential reservoir units on the cross sections into intervals of similar petrophysical character (flow units) using log data and, if available, porosity–permeability data. Categorize each flow unit by port type as mega-, macro-, meso-, or microporous.
4	Calculate water saturation (S_w) of intervals that ... • Are productive • Had shows • Are potential reservoirs Annotate the log intervals with S_w values.
5	Estimate the height above free water for zones that appear to have oil or gas.
6	Analyze the fluid data in the context of the petrophysical data. • Do S_w values, shows, and fluid pressures make sense in context with other geological data, including hydrocarbon column height? • Do the shows or S_w values indicate the presence of an updip or downdip trap?
7	Determine whether a relationship exists between the development of reservoir-quality rocks, seal-quality rocks, and lithofacies that can be used to predict location and economic viability of prospective traps.

Example: Calibrating logs to cores and shows

Posting core porosity, permeability, and pore throat radius (r_{35}) data directly on wireline logs next to lithofacies descriptions and show data helps us decide about exploitation for stratigraphic traps. In the figure below, the live oil stain in macroporous strata indicates the direction to move updip. The only macroporous strata present is within an algal mound facies developed in this parasequences at relative highstand. Microporous dolomites comprising the lower portions of the parasequences have poor reservoir characteristics, despite high porosity readings on the logs. Thus, the target of interest is the highstand mound facies.

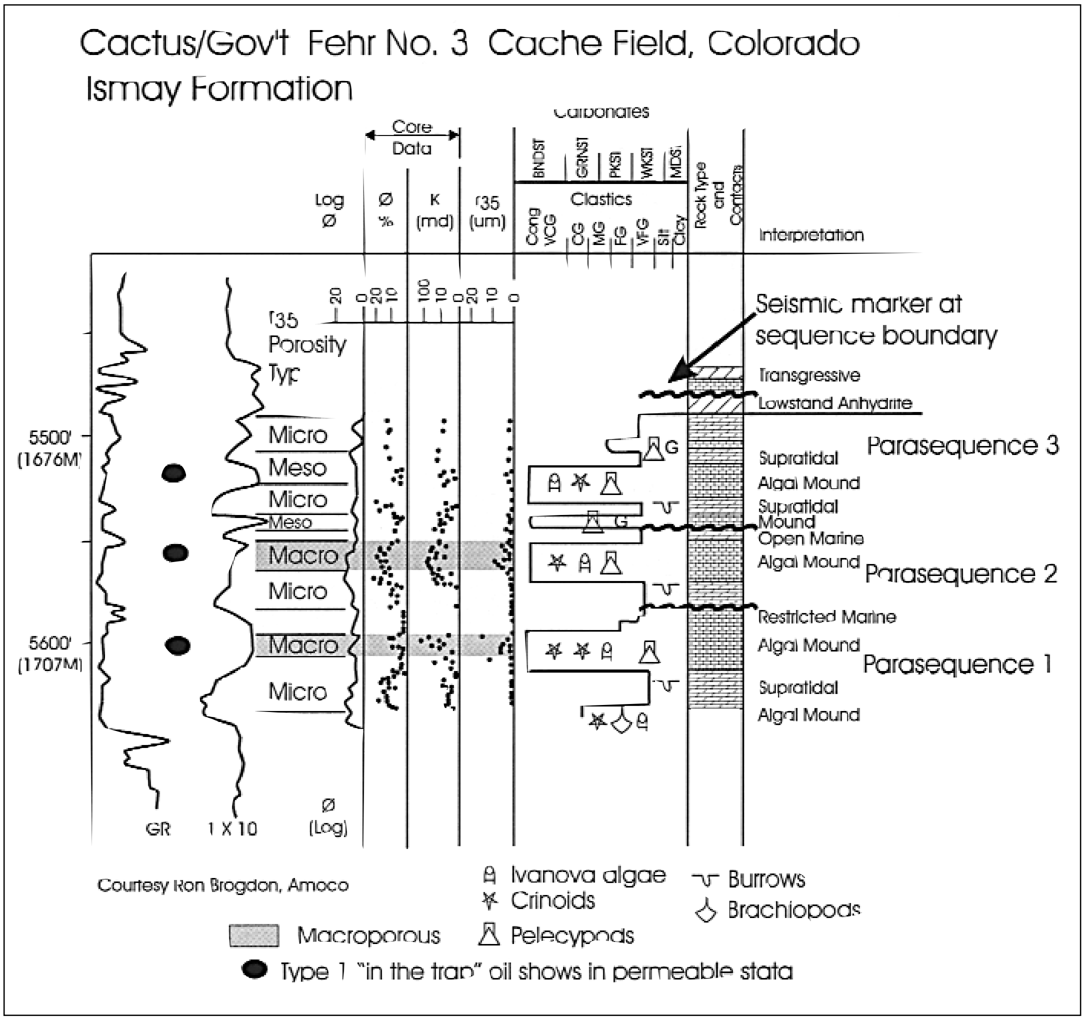


Figure 21–31.

Example: Using pressures

Reservoir scale discontinuities often cannot be detected by primary trapping geometries from sequence stratigraphy alone. Within channel systems of the Lower Cretaceous Mannville Group (Alberta, Canada), fluids distributions may be complex. High-resolution definition of the discrete traps may be possible only by integrating more data.

The figure to the right shows two distinct pressure regimes coinciding with discrete channel systems, delineated with pressure–depth plots. For additional information, refer to Dahlberg (1982).

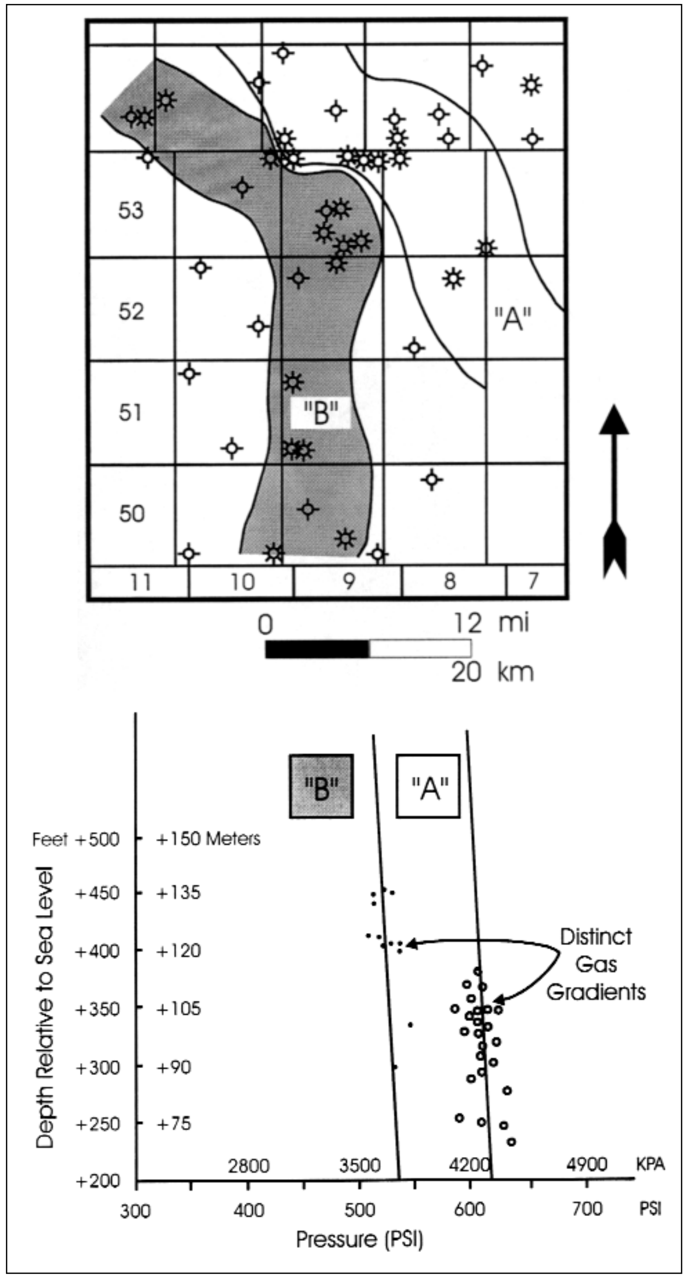


Figure 21–32. From Putnam and Oliver, 1980; courtesy Canadian Society of Petroleum Geologists. Map courtesy Eric Dahlberg.

Section E

Basin-Fill and Trap Analysis

Introduction

A whole basin or part of a basin can be analyzed for stratigraphic trap potential using the sequence stratigraphy approach. Basin-fill analysis is looking for stratigraphic or combination traps by combining paleogeography with the results of the geometric and facies analysis.

In this section

This section contains the following topics.

Topic	Page
Procedure for Basin-Fill Analysis	21–50
Mapping Paleogeography	21–52
Mapping Unconformities	21–53
Analyzing Depositional Sequences for Traps	21–56

Procedure for Basin-Fill Analysis

Objective

The objective of basin-fill analysis is to integrate sequence stratigraphy, geometrical analysis, seismic facies analysis, and lithofacies analysis to produce paleogeographic maps of depositional sequences.

Procedure

Below is a suggested procedure for basin-fill analysis.

Step	Action
1	Make a chronostratigraphic chart for the basin.
2	Combine sequence stratigraphic interpretations from seismic sections with sequence stratigraphic interpretations from well log cross sections.
3	Make paleogeographic maps of depositional sequences.
4	Identify the best locations for traps using a combination of paleogeography and sequence stratigraphy.

Chronostratigraphic charts

A chronostratigraphic chart is a correlation chart with geologic time as the Y-axis and distance across the area of interest as the X-axis. A dip-oriented chronostratigraphic chart should be made. But we also should consider making strike-oriented chronostratigraphic charts, depending on the complexity of the stratigraphic section. A chronostratigraphic chart shows the following (Mitchum and Vail, 1977):

- Apparent geologic time of each sequence and time gaps between sequences
- Relationships of sequences to bounding unconformities, highlighting areas of onlap, downlap, toplap, and truncation
- Relationships and correlation of parasequences to a sequence
- Distribution of facies

Chronostratigraphic charts aid in stratigraphic mapping by showing facies relationships across the basin in terms of time so that paleogeographic maps can be made. They are also useful for structural analysis.

Procedure for Basin-Fill Analysis, continued

Chronostratigraphic charts (continued)

Below is an example of a chronostratigraphic chart (A) correlated with a chart showing relative sea level changes (B).

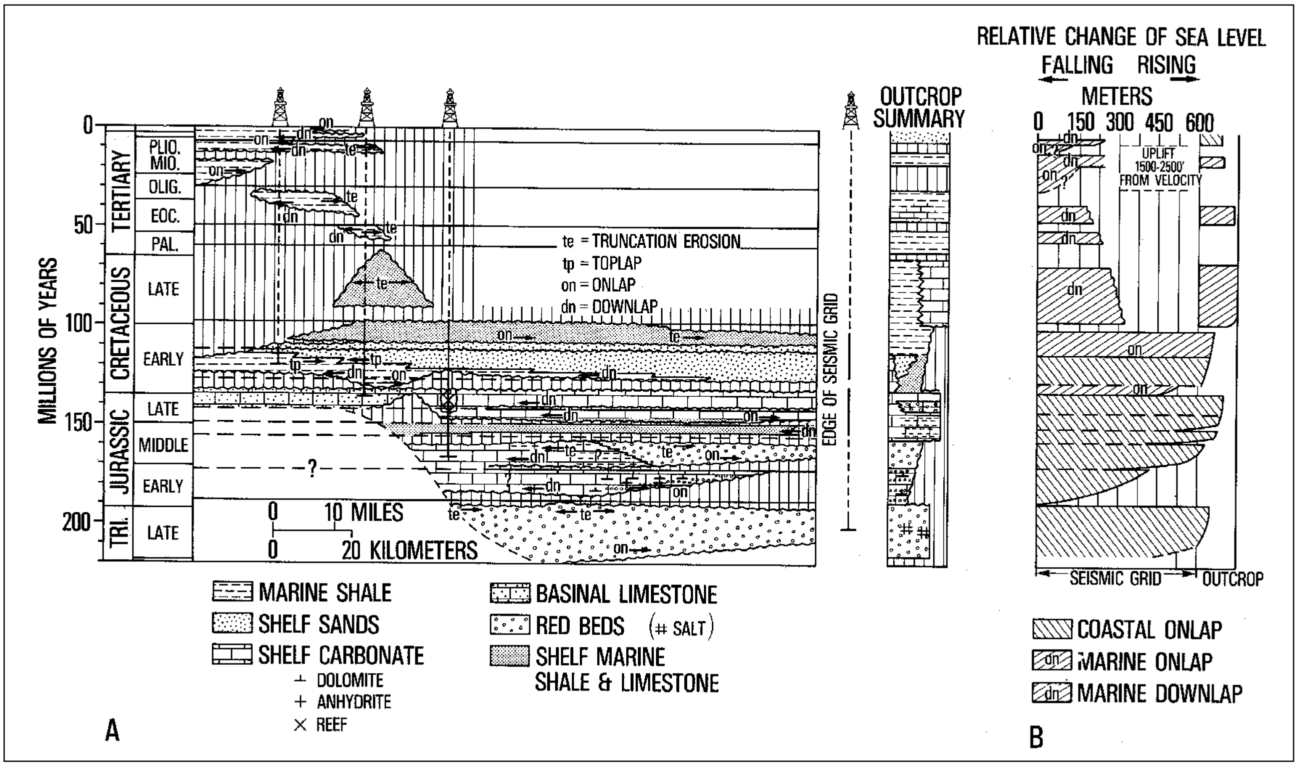


Figure 21–33. From Mitchum and Vail, 1977; courtesy AAPG.

Combining well and seismic data

Combining well and seismic data is simple once the correlation between the two is established. Synthetic seismograms establish these correlations. By combining lithofacies with seismic facies, stronger interpretations of the sedimentary section can be made away from well control. Seismic facies allow accurate correlation of lithofacies between wells. Lithofacies allow more detailed interpretation of seismic parameters, such as reflection patterns.

Mapping Paleogeography

Introduction

Paleogeographic maps are the end product of the sequence stratigraphic analysis. Favorable sites for deposition of reservoir, seal, and source rocks can be ascertained from paleogeographic maps.

Procedure

The table below outlines a procedure for making paleogeographic maps.

Step	Action
1	With objectives in mind, choose intervals to map. Is the target within one depositional sequence? Is the target the entire section?
2	Choose the level of detail. Do you need to map the paleogeography at the level of a depositional sequence or a systems tract?
3	Construct paleogeographic maps using all available information.

Example

Below is a seismic facies map and the corresponding paleogeographic map of the Middle Miocene Taranaki basin, offshore western New Zealand. The paleogeographic map depicts lithofacies and thicknesses in two-way time.

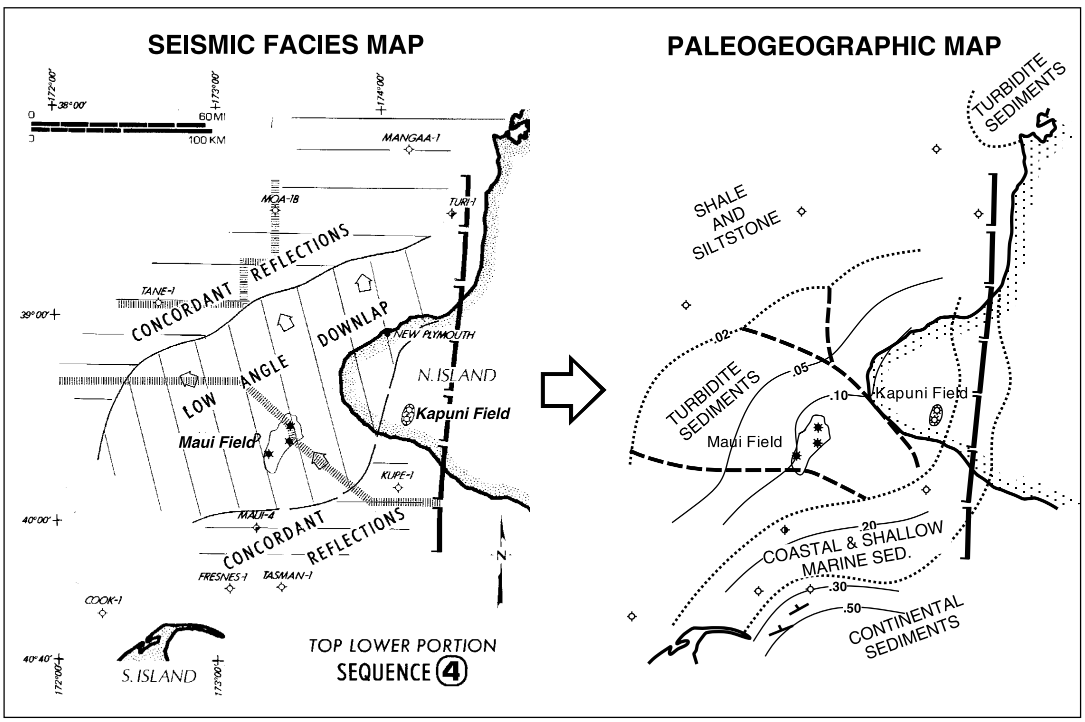


Figure 21–34. From Bally, 1987; courtesy AAPG.

Mapping Unconformities

Introduction

Mapping unconformities (sequence boundaries) is part of an effective exploration effort. Facies, porosity systems, and hydrocarbon shows are evaluated in context with an unconformity surface to predict trap location. Traps can be located above (onlap traps) or below (truncation traps) the unconformity. Seals, reservoir-quality rocks, and shows should be evaluated in terms of their relationship to the unconformity (see Dolson et al., 1994).

Procedure: Mapping unconformities

Follow these suggested steps to map unconformities for prospects.

Step	Action
1	Map subcrop and supercrop lithology and formations.
2	Make an isopach map from the unconformity to a flat datum above or below the unconformity to define paleotopography or paleostructure (see Figure 21–35).
3	Identify the best locations for truncation or onlap traps on the basis of the location seal and reservoir-quality rocks.

Making isopachs

The diagrammatic cross section below shows how to isopach above and below an unconformity. For more explanation, see Busch (1974).

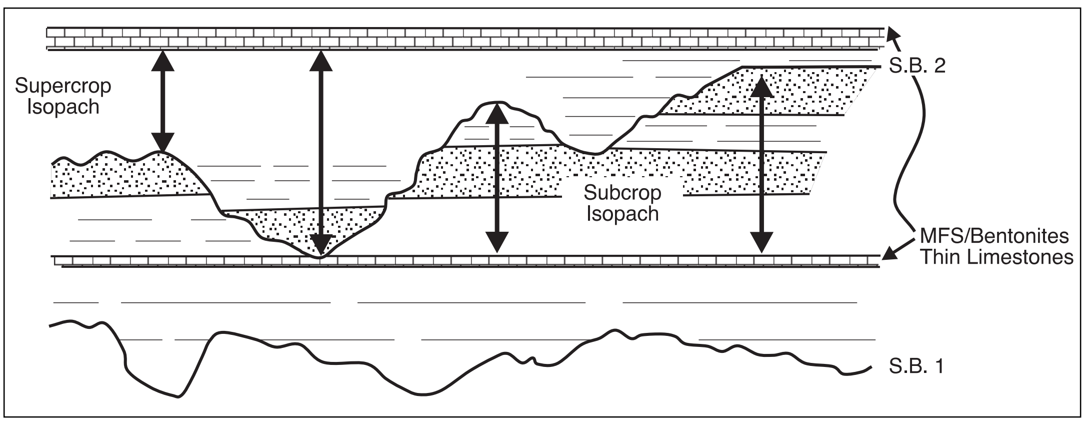


Figure 21–35.

Subcrop and facies mapping example

The Lower Cretaceous Cutbank Sandstone is the largest valley-fill trap in the Rocky Mountains (180 million BOE recoverable) (Dolson et al., 1993). The trap (illustrated below) is a combination valley wall and fossil oil–water contact trap. In this example, a flat datum within the Jurassic Sawtooth Formation was picked as the lowermost datum. Where the Sawtooth Formation is absent by onlap, the erosional top of the Mississippian was used, introducing some error on a local scale. "Thicks" are generally paleohills, and "thins" are incised valleys, although the "thick" to the west of the field is also caused by syndepositional westward thickening of the Jurassic section.

Mapping Unconformities, continued

Subcrop and facies mapping example (continued)

Below are subcrop isopach and formation/lithology maps and a cross section whose location is shown on the isopach map. Dashed and hachured areas are shale; stippled areas are sandstone. The arrows on cross section A-A' show the subcrop isopach interval. The north–south trending isopach thin and shaded area on the maps shows the location of the giant Cutbank field.

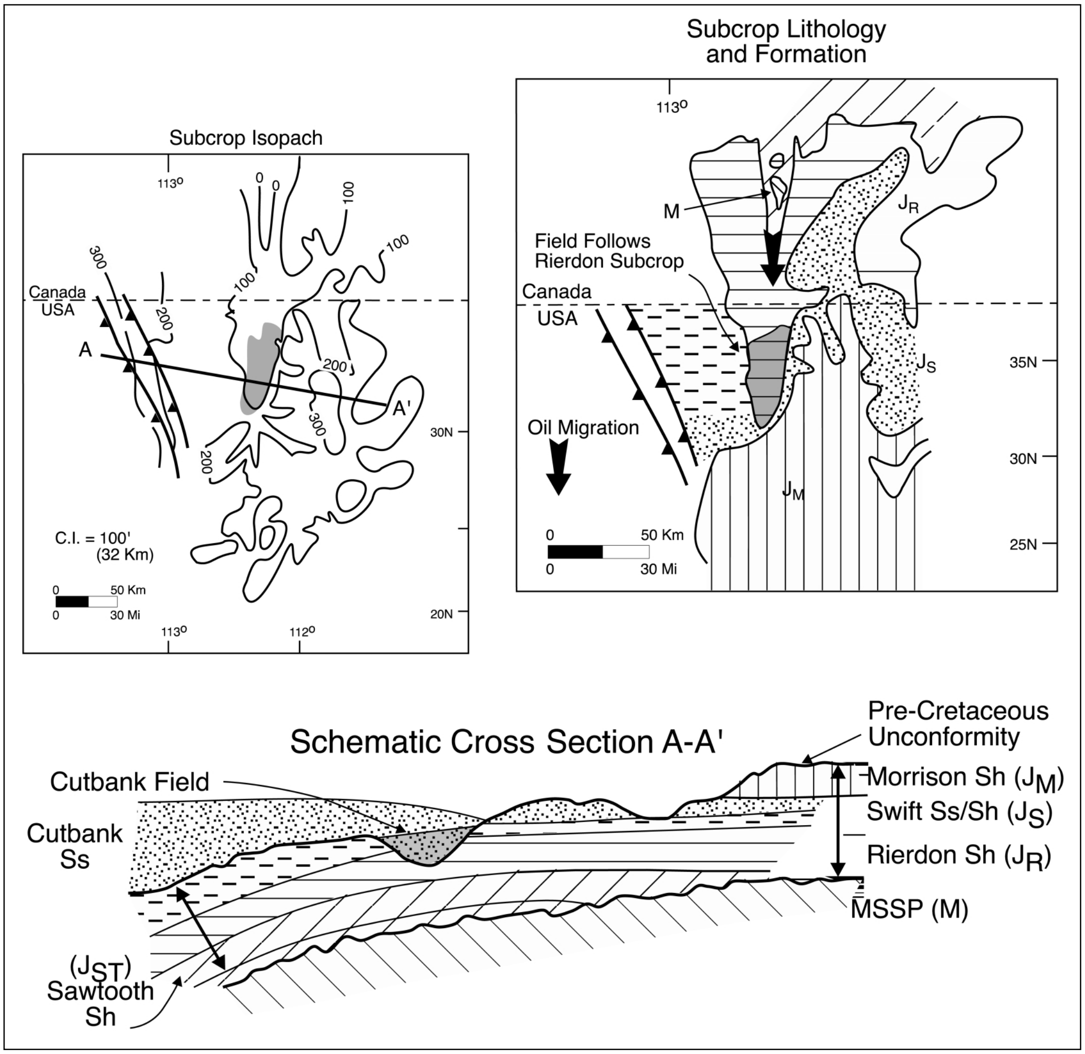


Figure 21–36. Dolson et al., 1993; courtesy Mountain Geologist.

Using subcrop maps to analyze seals

The subcrop lithology and formation map in Figure 21–36 illustrates where regional bottom and lateral seals are located. The trap is found where the porous Cutbank Sandstone abuts impermeable Jurassic shales. Where the Cutbank Sandstone abuts the permeable Swift Sandstone, leakage occurs updip. Oil migrates into the Cutbank where the valley bevels northward into a migration path at the top of the Mississippian strata.

Using subcrop maps to predict valley fill

Subcrop maps also help us predict lithologic content of the supercropping valley networks. In the example above, fine-grained sandstone and shale entered the Cutbank system from the east and south from eroding hills comprised of fine-grained Morrison and Swift strata. Coarse-grained gravels are confined exclusively to the main alluvial-fan system that eroded Paleozoic strata to the west.

In the Muddy Formation of the Western Interior of the United States, many shale-filled valleys occur where local tributaries have only subcropping Skull Creek Shale for a provenance. These valleys can form seals for subcropping reservoirs (Dolson et al., 1991; Dolson and Muller, 1994). Within deep basins, where the location of coarse gravels may be a primary reason to retain or create porosity, accurate regional reconstructions of erosional networks and their provenance areas are a must (Putnam and Oliver, 1980).

If the sequences are thick enough to image, chaotic seismic signatures within the valley may also suggest reservoir fill; smooth, parallel reflectors suggest shale fill.

Analyzing Depositional Sequences for Traps

Introduction

We can reasonably predict the location of stratigraphic or combination traps using the cross sections, seismic sections, and maps generated during an analysis of the seismic stratigraphy of a basin. This is especially true in basins containing oil or gas traps that can be used as analogs. Sequence stratigraphy, interpreted from seismic, well, and outcrop data, is an effective concept for assessing the quality and location of source, seal, and reservoir rocks. However, most researchers caution against blindly applying published sequence stratigraphic models (Handford and Loucks, 1993; Weimer and Posamentier, 1993). Exxon workers (Van Wagoner, 1990; Sarg, 1988) made assumptions in the models they developed, mainly based on Gulf Coast geology, that might not have universal application. Any model of sequence stratigraphy used for exploration purposes should be based on local geology. Locally based models make more effective exploration tools.

Procedure

Analyzing sequences for stratigraphic or combination traps is simply looking for stratigraphic changes, such as updip pinch-outs of rocks with reservoir potential or mounds of reservoir-quality rocks, in the context of a depositional sequence. Knowing where the target interval and area are within a depositional sequence gives us the ability to predict the presence of certain trap types. Follow the procedure outlined below to predict the location of traps within a sequence.

Step	Action
1	Using seismic lines and/or log cross sections, determine the systems tract type for intervals of interest, i.e., lowstand, transgressive, or highstand.
2	Identify potential seal- and reservoir-quality rocks using seismic facies and lithofacies shown on maps and cross sections.
3	In areas with juxtaposed reservoir- and seal-quality rocks, look for trapping geometries.

Transgressive and highstand systems tracts

Accommodation rates are high during transgressive–early highstand episodes of sea level, forming thick reservoirs of excellent quality. Shales in the upper transgressive systems tract and lower highstand systems tract are generally high-quality seals. Updip and bottom seals can be a problem for stratigraphic traps. Unconformity truncations, onlapping sands, and mounded shoreline sands form stratigraphic traps. Siliciclastics of the late highstand generally are poor reservoirs. Excellent source rocks are associated with the starved portion of the transgressive and early highstand systems tracts. Coals and terrestrial source rocks also are associated with the transgressive and early highstand systems tracts.

Lowstand systems tracts

During lowstands of sea level, sedimentation rates are high. Therefore, organic source potential is generally low. Where depositional sites are euxinic, source potential is higher. Even so, total organic carbon rarely exceeds 1% (Vail, 1987). Reservoir sands can be thick because they tend to aggrade as well as prograde.

Analyzing Depositional Sequences for Traps, continued

Lowstand systems tract traps

The diagrammatic cross section that follows and the corresponding table describe six potential trap types associated with the lowstand systems tract.

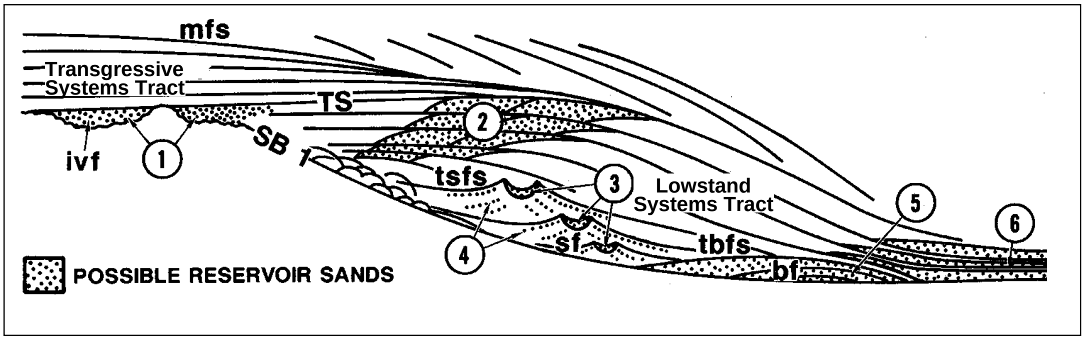
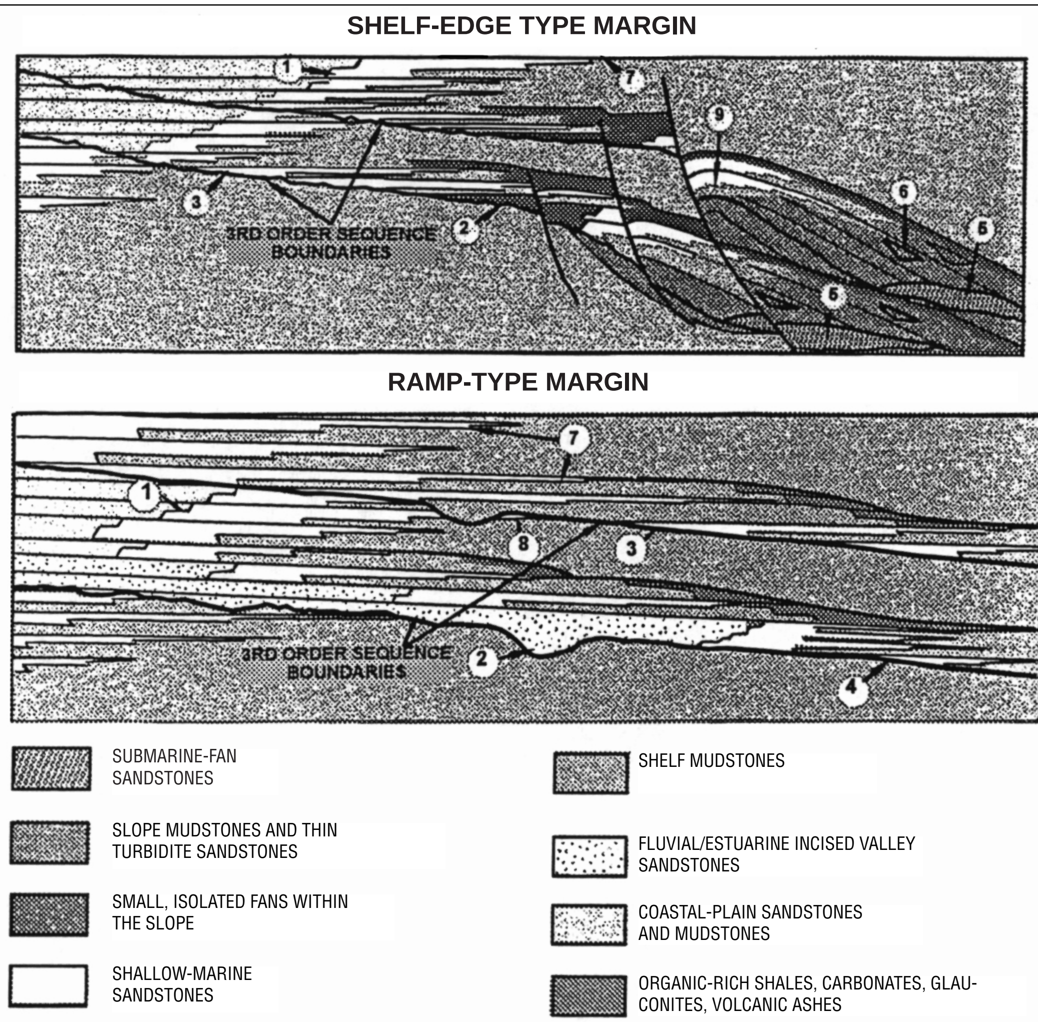


Figure 21–37. From Vail, 1987; courtesy AAPG.

No.	Facies	Trap Description
1	Incised valley sands	Excellent reservoirs. Traps form where valley incises underlying coastal plain shales.
2	Coastal belt sands	Good reservoirs, commonly very thick. Rollover traps common. Strat traps depend on undip seal. If underlying unit is impermeable, they are present where onlapping sands pinch out below preceding shoreline break.
3	Channel/overbank channel sands	Excellent reservoirs. Seal provided by toes of overlying lowstand wedge.
4	Overbank sands	Poor reservoirs. Seal provided by toes of overlying lowstand wedge.
5	Mounded basin floor fan sands	Sands thin or pinchout over contemporaneous highs. Strat traps depend on top and bottom seal. Overlying slope fan not a good seal. Best traps pinch out in a basinward direction.
6	Shingled toe of lowstand prograding wedge sands	Good reservoirs. In sandy systems, basin floor fans are shingled and pinch out between the shale toes of lowstand prograding wedge.

Plays in different margin types

Different margin types in basins have different play types determined by the geometry and history of the margin. The figure below shows play types for shelf-edge and ramp margins.



NO.	PLAY TYPE	RESERVOIR
1.	Updip pinchout	Beach or deltaic sandstones
2.	Incised valley	Braided-stream or estuarine sandstones
3.	Shelf onlap	Beach, deltaic, estuarine, or subtidal to tidal-flat sandstones
4.	Basinally restricted onlap	Deltaic sandstones
5.	Submarine fan	Submarine-fan turbidite sandstones
6.	Lowstand wedge	Small, areally restricted fans — composed of thin turbidite sandstones
7.	Downdip pinch-out	Deltaic, beach, or subtidal sandstones (need structural tilt)
8.	Truncation	Beach or deltaic sandstones

Figure 21–38. From Van Wagoner et al., 1990; courtesy AAPG.

Example: Integrating petrophysics and geology

Unpublished data (courtesy Amoco Production Company) derived from cores and seismic data were used to build an integrated lithofacies map. The figure below is a cross section representing the reservoir properties from representative capillary pressure data. The facies belts shown in the map above the cross section were deposited during maximum highstand of the Ismay (Pennsylvanian) carbonates. The facies are superimposed on an isopach map of the highstand systems tract. Test and show data overlain on the map show that significant reservoirs are restricted generally in the *Ivanovia* algal mound buildups, which flank a highstand basin shown in gray.

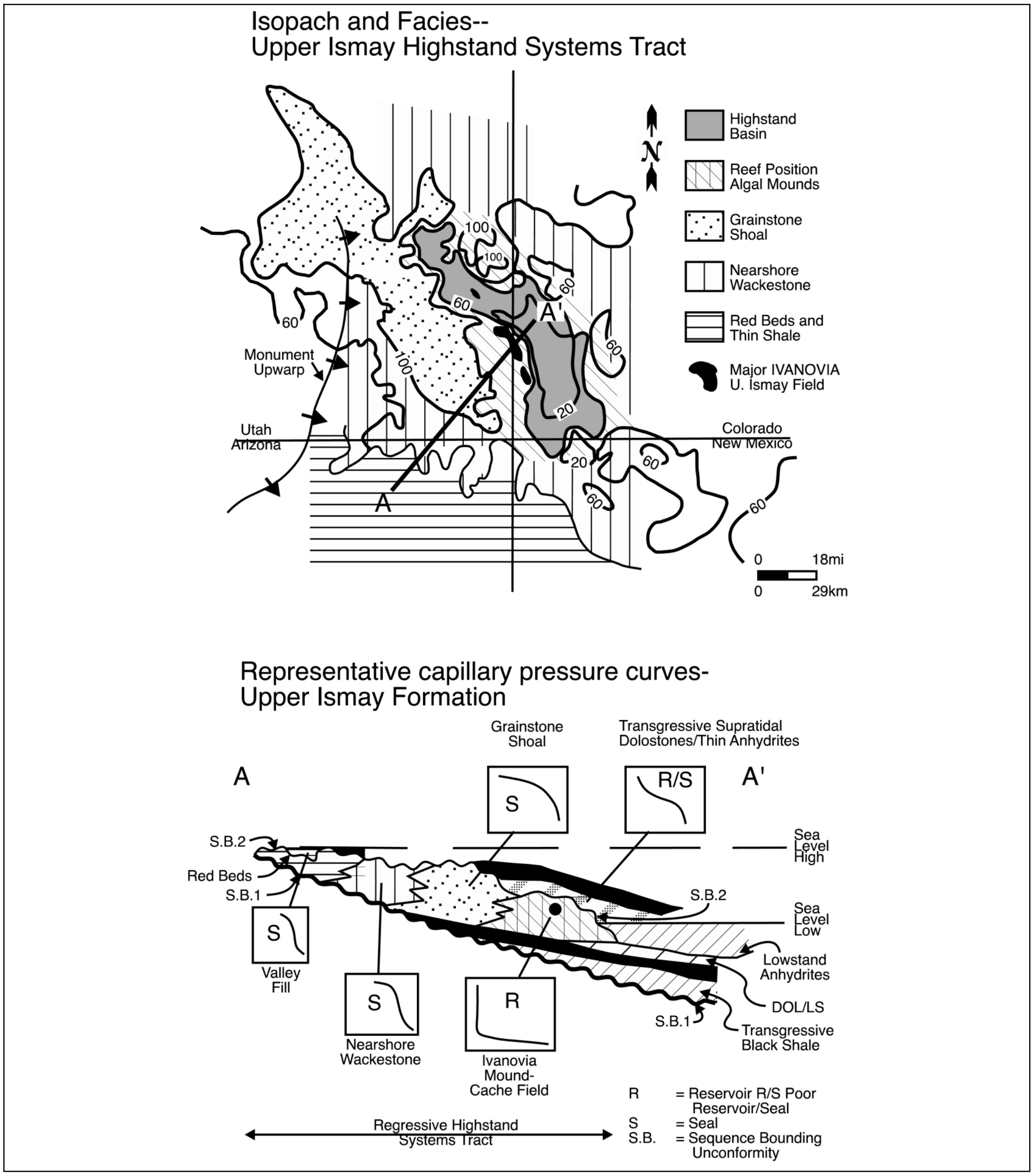


Figure 21–39.

Section F

Diagenetic Modifications of Stratigraphic Traps

Introduction

Diagenetic modifications to primary facies occur in most hydrocarbon accumulations. Understanding diagenetic production controls in existing fields and exploration controls for new fields is an important part of any geologist's role. In mature provinces, these traps form the dominant remaining play type. Although primary facies may exert strong control on diagenetic modifications, diagenetic changes can cross-cut these facies and be very difficult to predict.

In this section

This section contains the following topics.

Topic	Page
Types of Diagenetic Traps	21–61
Criteria for Recognizing Diagenetic Traps	21–62
Using Petrological Information	21–64

Types of Diagenetic Traps

Introduction

Diagenetic traps are created by pore throat modifications of primary facies. They can also be created by changes in fluid type within the pore system.

Categories

Diagenetic traps occur in two basic categories: early or near-surface traps and late-burial traps.

Early or near-surface diagenetic traps are created by the following:

- Reservoir destroyed by paleosols, meteoric cementation, karsting, cave development, and/or sediment infill
- Reservoir enhanced by paleo-groundwater movement and/or karsting

Late burial diagenetic traps are created by the following:

- Bottom seal generated below oil–water contacts by late cementation
- Primary porosity preserved due to selective cementation and/or early hydrocarbon emplacement
- Secondary porosity created by cement and/or matrix dissolution

The diagram below shows cross sections of diagenetic trap types.

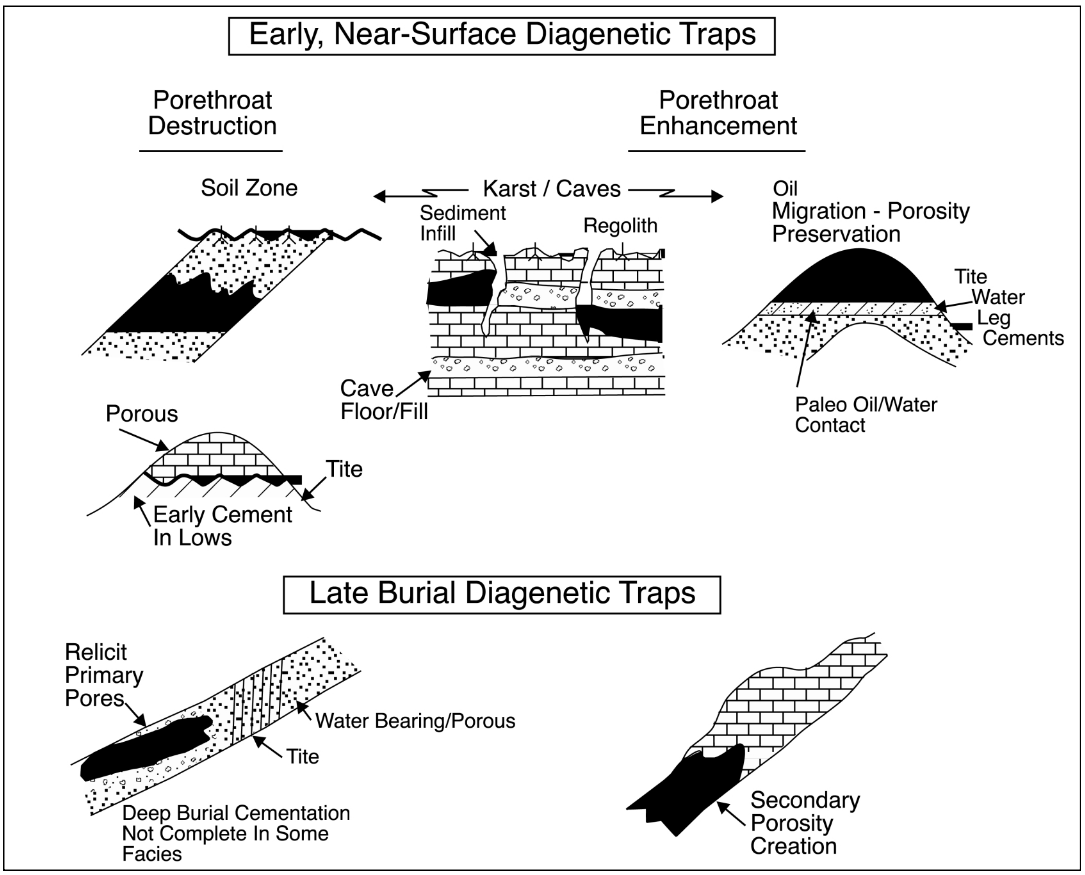


Figure 21–40.

Criteria for Recognizing Diagenetic Traps

Introduction

It is important early on in a play if diagenetic changes play a major role in trap modification. Test, production, geochemical, and show data provide the best criteria to recognize diagenetic modifications.

General geologic indications

Diagenetic traps can exist in the company of the following geologic indicators:

- Geologic setting conducive to development of paleotopographic relief
- Unconformities present
- No relationship between present-day depth and hydrocarbon production for a given zone
- Hydrocarbon accumulations in the absence of structural closure and not following closures created by primary facies changes

Petrographic indicators

Following are petrographic indicators of the potential presence of diagenetic traps:

- Early, pervasive, prehydrocarbon cements present updip from known production within a given facies (updip seal vs. downdip reservoir)
- Late, deep-burial cements or fabrics present, such as saddle or nonplanar dolomite, ferroan poikilotopic calcite, and anhydrite
- Abrupt vertical change in the amount of deep-burial cements present but not coincident with a change in depositional fabric (paleo oil–water contacts)
- Secondary porosity present but not related to subaerial exposure (subsurface deep burial dissolution)
- Zones of secondary porosity interbedded with tight rock in a depositionally homogeneous facies

Production indicators

The following indicate from field production the presence of diagenetic traps.

- Field boundaries within a given formation not coincident with structural closure or facies boundaries
- Tilted oil–water contacts present
- Adjacent structures not in pressure communication
- Pressures in oil-charged reservoirs unusually high
- Most of the wells characterized by high initial potential followed by rapid, sharp decline in flow rates; water cut typically low

Example: Diagenetic trap

Weyburn field, Alberta, is an example of a giant diagenetic trap (1 billion BOE). Primary trap geometries appear to be along the updip termination of the Midale dolomite above the potential bottom seal of the Frobisher anhydrite and beneath the top seal of the Mesozoic section. If only these trapping geometries were used to locate the trap, sequence stratigraphic mapping initially would not have located the trap. However, microporous dolomites are present near the Mesozoic sequence boundary in the updip portion of the Midale dolomite. These Mesoporous dolomites downdip form the reservoir facies.

Criteria for Recognizing Diagenetic Traps, continued

Example: Diagenetic trap (continued)

The microporous strata form the lateral seal. The sinuous updip edge is a large waste zone that contains live oil shows in microporous strata, indicating the accumulation is downdip.

The figure below contains a cross section, map, and summary of the field.

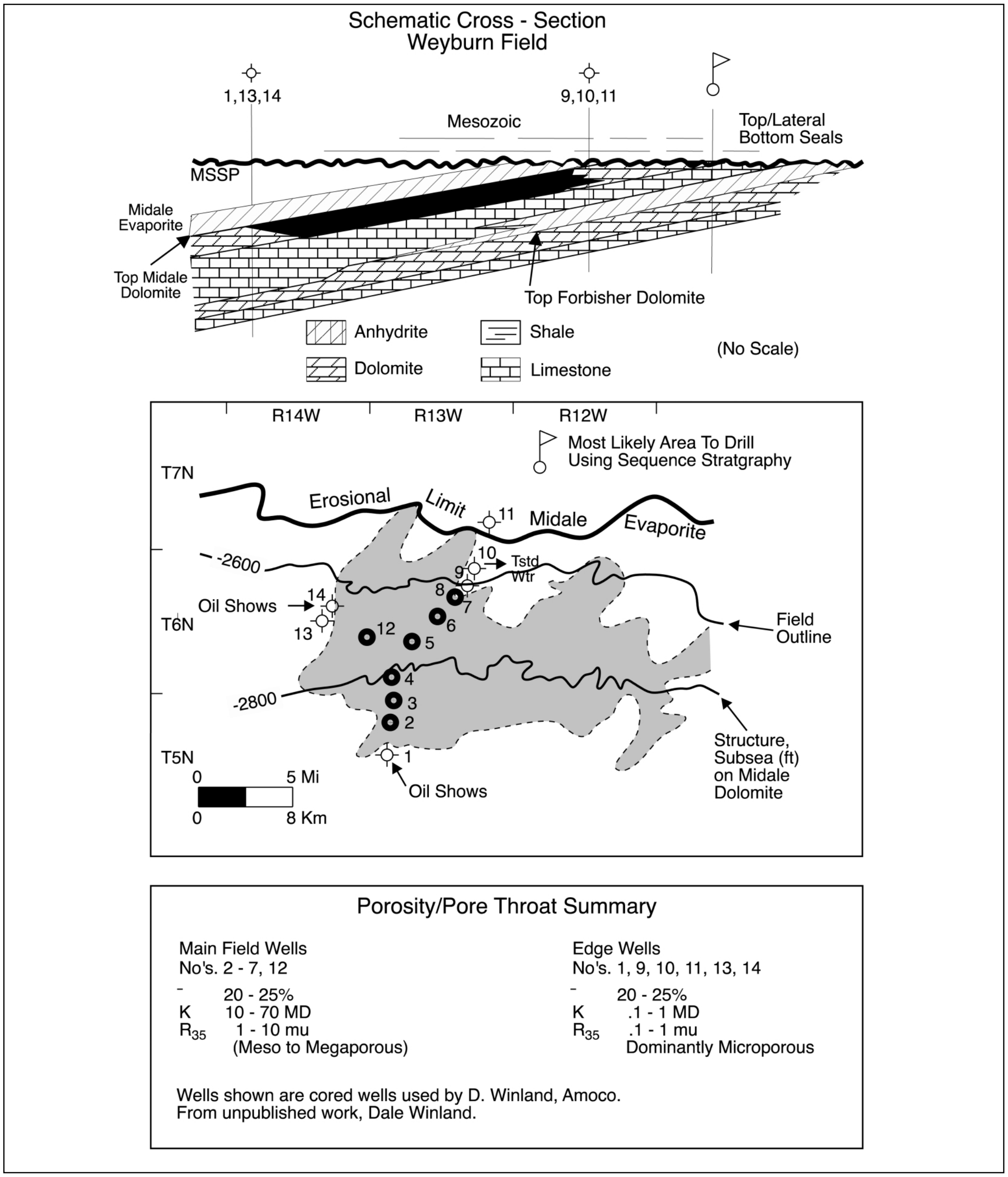


Figure 21–41. From Dale Winland, unpublished data.

Using Petrological Information

Introduction

Petrophysical, petrological, geochemical, production, pressure, and other subsurface data must be used to locate diagenetic traps. Petrological data, in conjunction with subsurface shows, can be a powerful tool in mapping and predicting traps.

Using petrological information

Petrographic data can provide information about migration timing, trap preservation, and facies vs. diagenetic controls on hydrocarbon distribution. The table below lists examples of applying petrological information.

Petrological Information	Exploration Significance	Exploration Application
Oil-filled fluid inclusions in reservoir or carrier beds	Indicates migration pathways and absolute timing of migration	Migration routes that existed during migration
Oil-filled fluid inclusions in seals	Indicates leaky seals and timing of leakage	Column height may be small and/or updip (spilled) accumulations may exist
Primary porosity preservation	Indicates facies patterns may control hydrocarbon distribution	Map depositional facies
Dissolution porosity present	Diagenesis may be critical for trap location; mineralogy and/or facies may control location of dissolution porosity	Use sequence stratigraphy, hydrologic, or thermal maturity models (refer to Tobin, 1991a,b; Read et al., 1995; Wilson, 1994)
Postmigration burial cements present	Indicates potential cementation of water leg	Map diagenetic facies

Example: Using cementation timing

In the example shown in the figure below, Cambrian sandstones in the Lublin basin (Poland) contain fluorescing oil inclusions trapped before the formation of quartz cements, which degraded the reservoir's quality. Oil traps could occur updip if seals were present during the migration event.

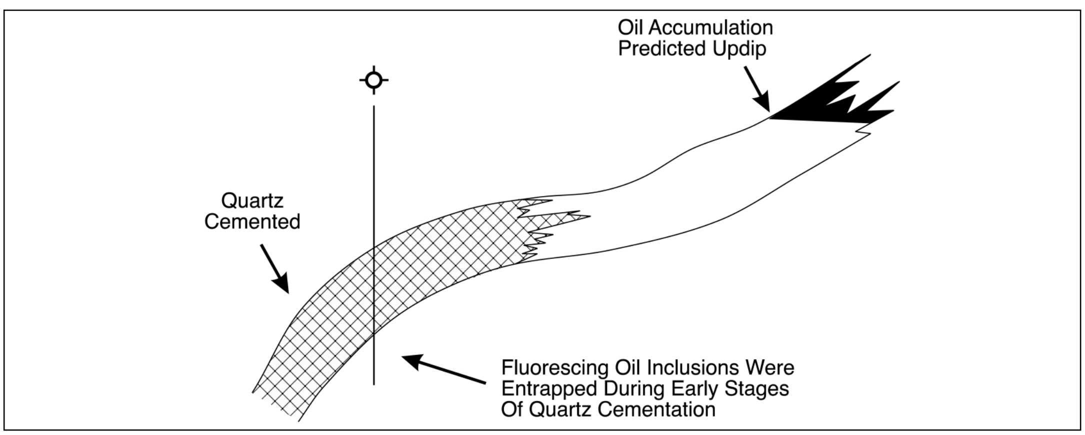


Figure 21–42. From Rick Tobin, unpublished data.

Section G
References

Aitken, J.F., and J.A. Howell, 1996, High-resolution sequence stratigraphy: innovations, applications and future prospects, *in* J.A. Howell and J.F. Aitken, eds., High Resolution Sequence Stratigraphy: Geological Society of London Special Pub. 104, p. 1–9.

Bahorich, M.S., and S.R. Bridges, 1992, The seismic sequence attribute map: Proceedings of the SEG 62nd Annual International Meeting and Exposition, New Orleans, p. 227–230.

_____ and S.L. Farmer, 1994, 3-D seismic discontinuity: the coherence cube for faults and stratigraphic features: U.S. patent 5,563,949; foreign patents pending.

_____ and _____, 1995, 3-D seismic discontinuity for faults and stratigraphic features: the coherence cube: The Leading Edge, vol. 14, no. 10, p. 1053–58.

Bally, A.W., ed., 1987, Atlas of Seismic Stratigraphy: AAPG Studies in Geology 27, vol. 1, 124 p.

Baum, G.R., and P.R. Vail, 1988, Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic basins, *in* C.K. Wilgus, B.S. Hastings, H.M. Posamentier, J. Van Wagoner, C.A. Ross, and G.C.St.C. Kendall, eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication 42, 407 p.

Brown, A.R., ed., 1999, Interpretation of Three-Dimensional Seismic Data, Fifth Edition, AAPG Memoir 42, 514 p.

Busch, D.A., 1974, Stratigraphic Traps in Sandstone—Exploration Techniques: AAPG Memoir 21, 174 p.

Dahlberg, E.C., 1982, Applied Hydrodynamics in Petroleum Exploration: New York, Springer-Verlag, 161 p.

Dolson, J.C., ed., 1991, Unconformity Related Hydrocarbon Exploitation and Accumulation in Clastic and Carbonate Settings: Rocky Mountain Assoc. of Geologists and Exploration Geoscience Institute (Colorado School of Mines) Core Workshop, Golden, Colorado, 297 p.

_____ and M.H. Franklin, 1991, Sub-Jurassic Sun River (Mississippian) diagenesis, reservoir properties and physical unconformity expression, Sweetgrass Arch, Montana, *in* J.C. Dolson, ed., Unconformity Related Hydrocarbon Exploitation and Accumulation in Clastic and Carbonate Settings: Rocky Mountain Assoc. of Geologists and Exploration Geoscience Institute (Colorado School of Mines) Core Workshop, Golden, Colorado, p. 195–208.

_____ and D.S. Muller, 1994, Stratigraphic evolution of the Lower Cretaceous Dakota Group, Western Interior, U.S.A., *in* M.V. Caputo, J.A. Peterson, and K.J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, U.S.A.: SEPM Rocky Mountain Section, p. 441–456.

_____ and J.T. Piombino, 1994, Giant proximal foreland basin non-marine wedge trap: Lower Cretaceous Cutbank Sandstone, Montana, *in* J.C. Dolson, M.L. Hendricks, and W.A. Wescott, eds., Unconformity-Related Hydrocarbons in Sedimentary Sequences: Rocky Mountain Assoc. of Geologists, p. 135–148.

_____, B. Steer, J. Garing, G. Osborne, A. Gad, and H. Amr, 1997, 3D seismic and workstation technology brings technical revolution to the Gulf of Suez Petroleum Company: The Leading Edge, vol. 16, no. 12, p. 1809–1817.

_____, D.S. Muller, M.J. Evetts, and J.A. Stein, 1991, Paleotopographic trends and production, Muddy Formation (Lower Cretaceous), Central and Northern Rocky Mountains: AAPG Bulletin, vol. 75, p. 405–435.

_____, J.T. Piombino, M.H. Franklin, and R. Harwood, 1993, Devonian oil in Mississippian and Mesozoic reservoirs—unconformity controls on migration and accumulation, Sweetgrass Arch, Montana: The Mountain Geologist, vol. 30, p. 125–146.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units: AAPG Bulletin, vol. 73, p. 125–142.

Gawthorpe, R.L., A.J. Fraser, and E.L. Collier, 1994, Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills: Marine and Petroleum Geology, vol. 11, no. 6, p. 642–658.

Gries, R., J.C. Dolson, and R.G.H. Reynolds, 1993, Structural and stratigraphic evolution and hydrocarbon distribution, Rocky Mountain Foreland, *in* R.W. Macqueen and D.A. Leckie, eds., Foreland Basins and Fold Belts: AAPG Memoir 55, p. 395–425.

Halbouty, M.T., ed., 1970, Geology of Giant Petroleum Fields: AAPG Memoir 14, 575 p.

_____, ed., 1980, Giant Oil and Gas Fields of the Decade 1968–1978: AAPG Memoir 30, 596 p.

_____, ed., 1982, The Deliberate Search for the Subtle Trap: AAPG Memoir 32, 351 p.

_____, 1990, Giant Oil and Gas Fields of the Decade 1978–1988: AAPG program abstracts, AAPG Stavanger Conference, Stavanger, Norway.

Handford, C.R., and R.G. Loucks, 1993, Carbonate depositional sequences and systems tracts—responses of carbonate platforms to relative sea-level changes, *in* R.G. Loucks and J.F. Sarg, eds., Carbonate Sequence Stratigraphy: Recent Developments and Applications: AAPG Memoir 57, p. 3–42.

Haq, B.U., J. Hardenbol, and P.R. Vail, 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change *in* C.K. Wilgus, B.S. Hastings, H.W. Posamentier, J. Van Wagoner, C.A. Ross, and G.C. St. C. Kendall, eds., Sea-Level Change: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 71–108.

Howell, J.A., and J.F. Aitken, 1996, eds., High-Resolution Sequence Stratigraphy: Innovations and Applications: Geological Society Publ. 104.

Hunt, D., and M.E. Tucker, 1993, The Mid-Cretaceous Urgonian platform of S.E. France, *in* J.A. Simo, R.W. Scott, and J.P. Masse, eds., Cretaceous Carbonate Platforms: AAPG Memoir 56, p. 409–453.

Hyne, N.J., 1995, Sequence stratigraphy: a new look at old rocks, *in* N.J. Hyne, ed., Sequence Stratigraphy of the Mid Continent: Tulsa Geological Society Special Publication 4, p. 5–20.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expressions, *in* C.K. Wilgus, B.S. Hastings, H.W. Posamentier, J. Van Wagoner, C.A. Ross, and C.G. St. C. Kendall, eds., Sea Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 47–69.

Loucks, R.G., and J.F. Sarg, eds., 1993, Carbonate Sequence Stratigraphy, Recent Developments and Applications: AAPG Memoir 57, 545 p.

Mitchum, R.M., P.R. Vail, and J.B. Sangree, 1977, Seismic stratigraphy and global changes in sea level, part 6: stratigraphic interpretations of seismic reflection patterns in depositional sequences, *in* C.E. Payton, ed., Seismic Stratigraphy and Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 117–133.

_____, J.B. Sangree, P.R. Vail, and W.W. Wornardt, 1993, Recognizing sequences and systems tracts from well logs, seismic data, and biostratigraphy: examples from the Late Cenozoic of the Gulf of Mexico, *in* P. Weimer and H.W. Posamentier, eds., Siliciclastic Sequence Stratigraphy, Recent Developments and Applications: AAPG Memoir 58, p. 163–197.

Posamentier, H.W., and P.R. Vail, 1988, Eustatic controls on clastic deposition II—sequence and systems tract models, *in* C.K. Wilgus, B.S. Hastings, H.W. Posamentier, J. Van Wagoner, C.A. Ross, and G.C.St.C. Kendall, eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication 42, p. 125–154.

Prosser, S., 1993, Rift-related linked depositional systems and their seismic expression, *in* G.D. Williams and A. Dobb, eds., Tectonics and Seismic Sequence Stratigraphy: Geological Society Special Publication 71, p. 35–66.

Putnam, P.E., and T.A. Oliver, 1980, Stratigraphic traps in channel sandstones in the Upper Mannville (Albian) of east-central Alberta: Canadian Society of Petroleum Geologists Bulletin, vol. 28, p. 489–508.

Ramzy, M., B. Steer, F. Abu-Shadi, M. Schlorholtz, J. Mika, J.C. Dolson, and M. Zinger, 1996, Gulf of Suez rift basin sequence models—part B: Miocene sequence stratigraphy and exploration significance in the central and southern Gulf of Suez: Proceedings of the 13th Petroleum Conference, the Egyptian General Petroleum Corp., vol. 2, p. 242–256.

Ravnas, R., and R.J. Steel, 1998, Architecture of marine rift basin succession: AAPG Bulletin, vol. 82, no. 1, p. 110–146.

Read, J.F., C. Kerans, J.F. Sarg, F.M. Wright, 1995, Milankovitch Sea-Level Changes, Cycles, and Reservoirs on Carbonate Platforms in Greenhouse and Ice-House Worlds: SEPM Short Course 35, 79 p.

Sarg, J.F., 1988, Carbonate sequence stratigraphy, *in* C.K. Wilgus et al., eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication 42, p. 155–181.

References, continued

Tobin, R.C., 1985, Reservoir development in Ellenburger group of West Texas—a diagenetic jambalaya: AAPG Bulletin, vol. 2, p. 312.

_____, 1991a, Diagenesis, thermal maturation and burial history of the Upper Cambrian Bonneterre Dolomite, southeastern Missouri: an interpretation of thermal history from petrographic and fluid inclusion evidence: Organic Geochemistry, vol. 17, no. 2, p 142–152.

_____, 1991b, Pore system evolution vs. paleotemperature in carbonate rocks: a predictable relationship?: Organic Geochemistry, vol. 17, no. 2, p. 271.

Underhill, J.R., and M.A. Partington, 1993, Use of genetic sequence stratigraphy in defining and determining and regional tectonic control on the "Mid-Cimmerian Unconformity"—implications for North Sea basin development and the global sea level chart, *in* P. Weimer and H.W. Posamentier, eds., Siliciclastic Sequence Stratigraphy, Recent Developments and Applications: American Association of Geologists Memoir 58, p. 449–484.

Vail, P.R., 1987, Seismic stratigraphy interpretation procedure, *in* A.W. Bally, ed., Atlas of Seismic Stratigraphy: AAPG Studies in Geology No. 27, p. 2.

Van Wagoner, J.C., 1995, Overview of sequence stratigraphic foreland basin deposits: terminology, summary of papers, and glossary of sequence stratigraphy, *in* J.C. Van Wagoner and G.T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64, p. ix–xxi.

Van Wagoner, J.C., et al., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* C.K. Wilgus et al., eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication 42, p. 39–45.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops: Concepts for High-Resolution Correlation of Time and Facies: AAPG Methods in Exploration Series No. 7, 55 p.

Weber, L.J., J.F. Sarg, and F.M. Wright, 1995, Sequence stratigraphy and reservoir delineation of the middle Pennsylvanian (Desmoinesian), Paradox basin and Aneth field, southwestern U.S.A., *in* J.F. Read, L.J. Weber, J.F. Sarg, and F.M. Wright, eds., Milankovitch Sea-Level Changes, Cycles, and Reservoirs on Carbonate Platforms in Greenhouse and Ice-House Worlds: SEPM Short Course No. 35, 79 p.

Weimer, P., and H.W. Posamentier, eds., 1993, Siliciclastic Sequence Stratigraphy, Recent Developments and Applications: AAPG Memoir 58, 492 p.

Wescott, W.A., and P.J. Boucher, 1998, Paleohydraulic characteristics of Late Miocene–Early Pliocene submarine channels in the Nile Delta, Egypt: AAPG Bulletin, vol. 82, p. 695.

Wilgus, C.K., B.S. Hastings, et al., eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication 42, 407 p.

Wilson, M.D., ed., 1994, Reservoir Quality Assessment and Prediction in Clastic Rocks: SEPM (Society of Sedimentary Geology) Short Course 30, 432 p.