Sequence Stratigraphy—A Global Theory for Local Success

No exploration technique flawlessly locates a potential reservoir, but sequence stratigraphy may come close. By understanding global changes in sea level, the local arrangement of sand, shale and carbonate layers can be interpreted. This enhanced understanding of depositional mechanics steers explorationists toward prospects missed by conventional interpretation.

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□***A seismic section interpreted to show the sandy interval*** *(yellow)* ***predicted using sequence stratigraphy. The heavy vertical line shows the well location.***

Conventional lithologic correlation maps formation tops by interpreting well log data alone. It looks at what is there without taking into account how it got there. Sequence stratigraphy combines logs with fossil data and seismic reflection patterns to explain both the arrangement of rocks and the depositional environment. Understanding the relationships between rock layers, their seismic expression and depositional environments allows more accurate prediction of reservoirs, source rocks and seals, even if none of them intersect the well (*above*).

Sequence stratigraphy is used mainly in exploration to predict the rock composition of a zone from seismic data plus distant, sparse well data. It also assists in the search for likely source rocks and seals. Experts believe that as more people learn the technique, it will become an exploitation tool for constraining the shape, extent and continuity of reservoirs.

Sequence Stratigraphy, Seismic Stratigraphy—How Many Stratigraphies Can There Be?

Stratigraphy is the science of describing the vertical and lateral relationships of rocks.[1] These relationships may be based on rock type, called lithostratigraphy, on age, as in chronostratigraphy, on fossil content, labeled biostratigraphy, or on magnetic properties, named magnetostratigraphy.

Stratigraphy in one form or another has been around since the 1600s. In 1669, Nicholaus Steno, a Danish geologist working in Italy, recognized that strata are formed as heavy particles settle out of a fluid. He also recognized that some strata contain remnants of other strata, and so must be younger. This conflicted with the widely held view that all sediments were deposited during the flood at the time of Noah. Steno developed three principles that form the basis of all stratigraphy—younger layers lie on top of older layers, layers are initially horizontal, and layers continue until they run into a barrier. His work was neither widely publicized nor remembered and is often credited to James Hutton (1726-1797) or Charles Lyell (1797-1875).

For 300 years after Steno, stratigraphers worked at unraveling the history of the earth, correlating fossils from one continent to another, assigning names, ages and eventually physical mechanisms to the creation of rock layers. By 1850, most of the major geologic time units had been named. By 1900, most layers had relative ages, and rock types had been associated with certain positions of the shoreline, which was known to move with time. Fine-grained rocks such as siltstones and shales were associated with calm, deep water, and coarse-grained, sandy rocks with energetic, shallow environments.

At the turn of the century, shoreline movement was attributed to tectonic activity—the rising and falling of continents. This view was challenged in 1906, when Eduard Suess hypothesized that changes in shoreline position were related to sea level changes, and occurred on a global scale; he called the phenomenon eustasy.[2] However, Suess was not able to refute evidence presented by opponents of his theory—in many locations there were discrepancies between rock types found and types predicted by sea level variation.

In 1961, Rhodes W. Fairbridge summarized the main mechanisms of sea level change: tectono-eustasy, controlled by deformation of the ocean basin; sedimento-eustasy, controlled by addition of sediments to basins, causing sea level rise; glacio-eustasy, controlled by climate, lowering sea level during glaciation and raising it during deglaciation. He recognized that all these causes may be partially applicable, and are not mutually incompatible. He believed that while eustatic hypotheses apply worldwide, tectonic hypotheses do not and vary from region to region. Fairbridge summarized the perceived goal at the time: "*We need therefore to keep all factors in mind and develop an integrated theory. Such an ideal is not yet achievable and would involve studies of geophysics, geochemistry, stratigraphy, tectonics, and geomorphology, above sea level and below.*"[3]

This brings us nearly to the present. In 1977, Peter Vail at Exxon and several colleagues published the first installments of such an integrated theory.[4] Vail developed a new kind of stratigraphy based on ideas proposed by L. L. Sloss—the grouping of layers into unconformity-bound[5] sequences based on lithology—and by Harry E. Wheeler—the grouping of layers based on what has become known as chronostratigraphy.[6] Vail's approach allowed interpreting unconformities based on tying together global sea level change, local relative sea level change and seismic reflection patterns. This methodology, named seismic stratigraphy, classifies layers between major unconformities based on seismic reflection patterns, giving a seismically derived notion of lithology and depositional setting.

Subsequent seismic stratigraphic studies in basins around the world produced a set of charts showing the global distribution of major unconformities interpreted from seismic discontinuities for the past 250 million years.[7] An understanding emerged that these unconformities were controlled by relative changes in sea level, and that relative changes in sea level could be recognized on well logs and outcrops, with or without seismic sections. This led to the interdisciplinary concept of sequence stratigraphy—a linkage of seismic, log, fossil and outcrop data at local, regional and global scales. The integrated theory sought by Fairbridge had arrived.

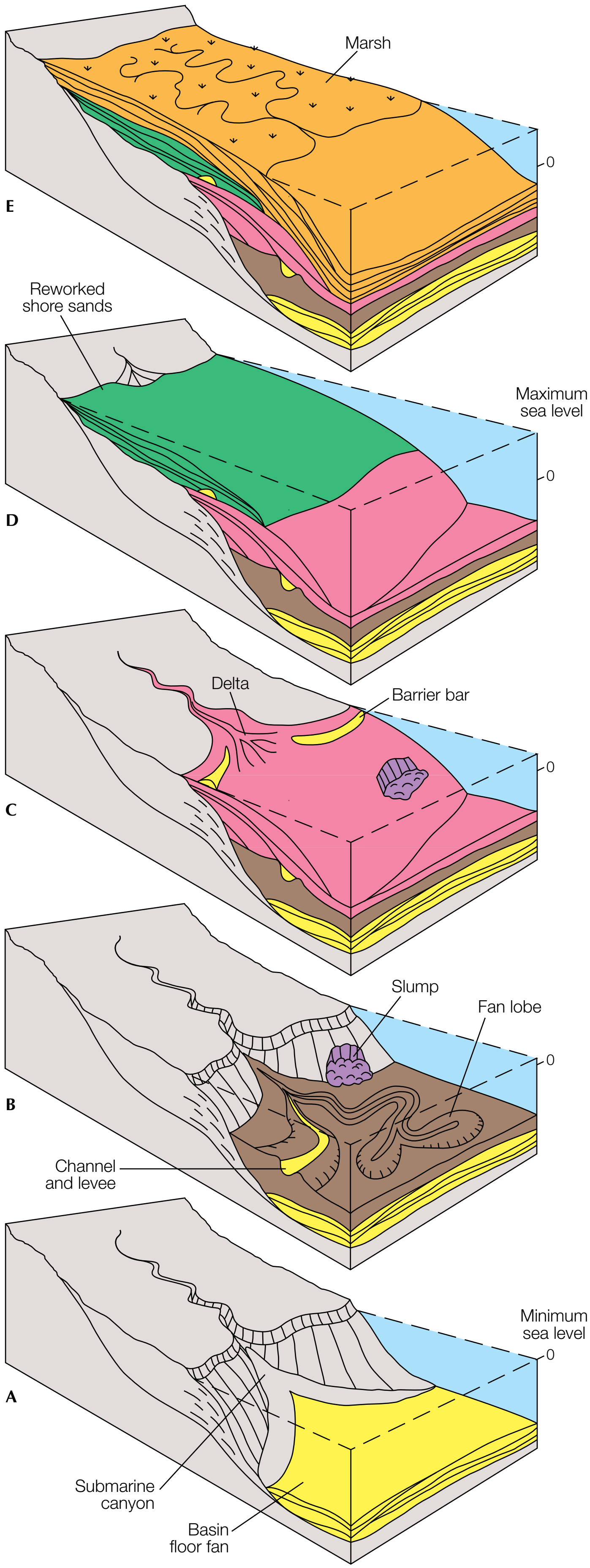
This article focuses on the subset of sequence stratigraphy that includes seismic data, and so falls under the heading of seismic sequence stratigraphy. The technique has been shown to work in a variety of settings, in some better than others. Attention here is on an environment where it has proved successful—sand and shale deposition on continental margins.

Building Blocks

The concepts that govern sequence stratigraphic analysis are simple. A depositional sequence comprises sediments deposited during one cycle of sea level fluctuation—by Exxon convention, starting at low sea level, going to high and returning to low. One cycle may last a few thousands to millions of years and produce a variety of sediments, such as beach sands, submarine channel and levee deposits, chaotic flows or slumps and deep water shales. Sediment type may vary gradually or abruptly, or may be uniform and widespread over the entire basin. Each rock sequence produced by one cycle is bounded by an unconformity at the bottom and top.[8] These sequence boundaries are the main seismic reflections used to identify each depositional sequence, and separate younger from older layers everywhere in the basin.

Composition and thickness of a rock sequence are controlled by space available for sediments on the shelf, the amount of sediment available and climate. Space available on the shelf—which Vail calls "shelfal accommodation space"—is a function of tectonic subsidence and uplift and of global sea level rise and fall on the shelf. For instance, subsidence during rising sea level will produce a larger basin than uplift during rising sea level. The distribution of sediment depends on shelfal accommodation, the shape of the basin margin—called depositional profile—sedimentation rate and climate. Climate depends on the amount of heat received from the sun. Climate also influences sediment type, which tends toward sand and shale in temperate zones and allows the production of carbonates in the tropics.

As an exploration tool, sequence stratigraphy is used to locate reservoir sands. In deep water basins with high sedimentation rates, sands are commonly first laid down as submarine fans on the basin floor (*next page, "A"*) and later as deposits on the continental slope or shelf (*next page, "B"*). But as sea level starts slowly rising onto the continental shelf, sands are deposited a great lateral distance from earlier slope and basin deposits.[9] Deposits during this time are deltaic sediments that build into the basin and deep water shales (*next page, "C"*). If the sediment supply cannot keep pace with rising sea level, the shoreline migrates landward and sands move progressively higher up the shelf (*next page, "D"*). Once sea



☐Sequence components in order of deposition, from bottom to top. The sequence begins when sea level relative to the basin floor begins to fall.

The first deposits, sand-rich fans, are laid down while sea level is falling to its lowest point (A).

As sea level bottoms out and begins to rise (B), sands and shale are deposited in fans on the continental slope. Submarine channels with levees may meander across the fan. Slumps are common.

The continuing rise in sea level (C) allows wedges of sediment to build into the basin, with sands near the shore, siltstones and shale basinward.

A rapid rise in sea level (D) moves sandiest sediments landward as beaches and sandbars.

Sea level then rises at a lower rate (E), allowing sediments to build basinward again. Sandy sediments are usually restricted to the nearshore margin.

Colors follow a convention used by Vail. In order of deposition, basin floor fans are yellow, slope fans are brown and submarine slumps are purple. River deltas that build out during low relative sea level are pink. Rocks associated with higher relative sea level—and usually less likely to be sandy—are green and orange. Within every part of a sequence, sand-prone zones are yellow.

level reaches a maximum for this cycle, sands will build basinward as long as sediment remains available (*left, "E"*). The sequence ends with a fall in relative sea level, marked by a break in deposition. The sequence repeats, however, as long as there is sediment and another cycle of rise and fall in relative sea level that changes the shelfal accommodation space (see "A Detailed View of Sequence Stratigraphy," *next page*).

(*continued on page 56*)

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1. For a review:

   Schoch RM: *Stratigraphy: Principles and Methods.* New York, New York, USA: Van Nostrand Reinhold, 1989.

2. Suess E: *The Face of the Earth*, vol 2. Oxford, England: Clarendon Press, 1906.

3. Fairbridge RW: "Eustatic Changes in Sea Level," in Ahrens LH, Press F, Rankama K and Runcorn SK (eds): *Physics and Chemistry of the Earth,* vol. 4. London, England: Pergamon Press Ltd. (1961): 99-185.

4. Vail PR and Mitchum RM: "Seismic Stratigraphy and Global Changes of Sea Level, Part 1: Overview," in Payton CE (ed): *AAPG Memoir 26 Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (1977): 51-52.

   Mitchum RM, Vail PR and Thompson S: "Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis," in Payton CE (ed): *AAPG Memoir 26 Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (1977): 53-62.

   Vail PR, Mitchum RM and Thompson S: "Seismic Stratigraphy and Global Changes of Sea Level, Part 3: Relative Changes of Sea Level from Coastal Onlap," in Payton CE (ed): *AAPG Memoir 26 Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (1977): 63-82.

   Vail PR, Mitchum RM and Thompson S: "Seismic Stratigraphy and Global Changes of Sea Level, Part 4: Global Cycles of Relative Changes of Sea Level," in Payton CE (ed): *AAPG Memoir 26 Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (1977): 83-98.

   Vail P, Todd RG and Sangree JB: "Seismic Stratigraphy and Global Changes of Sea Level, part 5: Chronostratigraphic Significance of Seismic Reflections," in Payton CE (ed): *AAPG Memoir 26 Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (1977): 99-116.

   Sangree JB and Widmier JM: "Interpretation of Depositional Facies From Seismic Data," *Geophysics* 44 (February 1979): 131-160.

5. An unconformity is a surface separating younger from older layers, along which there is evidence of erosion or a significant break in deposition.

6. Sloss LL: "Sequences in the Cratonic Interior of North America," *Geological Society of America Bulletin* 74 (1963): 93-113.

   Wheeler HE: "Time Stratigraphy," *American Association of Petroleum Geologists Bulletin* 42, no. 5 (May 1958): 1047-1063.

7. Haq BU, Hardenbol J and Vail PR: "Chronology of Fluctuating Sea Levels Since the Triassic," *Science* 235 (1987): 1156-1166.

8. In some cases the unconformity may correlate laterally with a conformity. A conformity is a surface that conforms to those above and below it, with no evidence of erosion or nondeposition.

9. In the case of the Gulf of Mexico, a 100-m rise in relative sea level would cause a 150-km landward shift of the shoreline:

   Matthews RK: *Dynamic Stratigraphy.* Englewood Cliffs, New Jersey, USA: Prentice-Hall, Inc. (1984): 394.

A Detailed View of Sequence Stratigraphy

The components of depositional sequences are called systems tracts. Systems tracts are divided into three groups according to relative sea level at the time of deposition—lowstand at low relative sea level, transgressive as the shoreline moves landward, and highstand at high relative sea level. Systems tracts are depositional groups that have a predictable stratigraphic order and predictable shapes and contents. A close look at systems tracts, their geometries and lithologies, shows how sequence stratigraphy can be used to foretell reservoir location and quality.

Each systems tract exhibits a characteristic log response, seismic signature and paleontologic fingerprint, and performs a predictable role in the oil and gas play—reservoir rock, source rock or seal. Gamma ray (GR) and spontaneous potential (SP) logs are expected to read low in sands and high in shales. Resistivity logs show the reverse, reading high in hydrocarbon-filled sands and low in shales.

Apparent layering interpreted on seismic sections—called stratal patterns—is determined by tracing seismic reflections to their terminations. The termination is categorized by its geometry and associated with a depositional style. Fossils are described by their abundance, diversity and first or last occurrence, allowing dates to be determined based on correlation with global conditions.

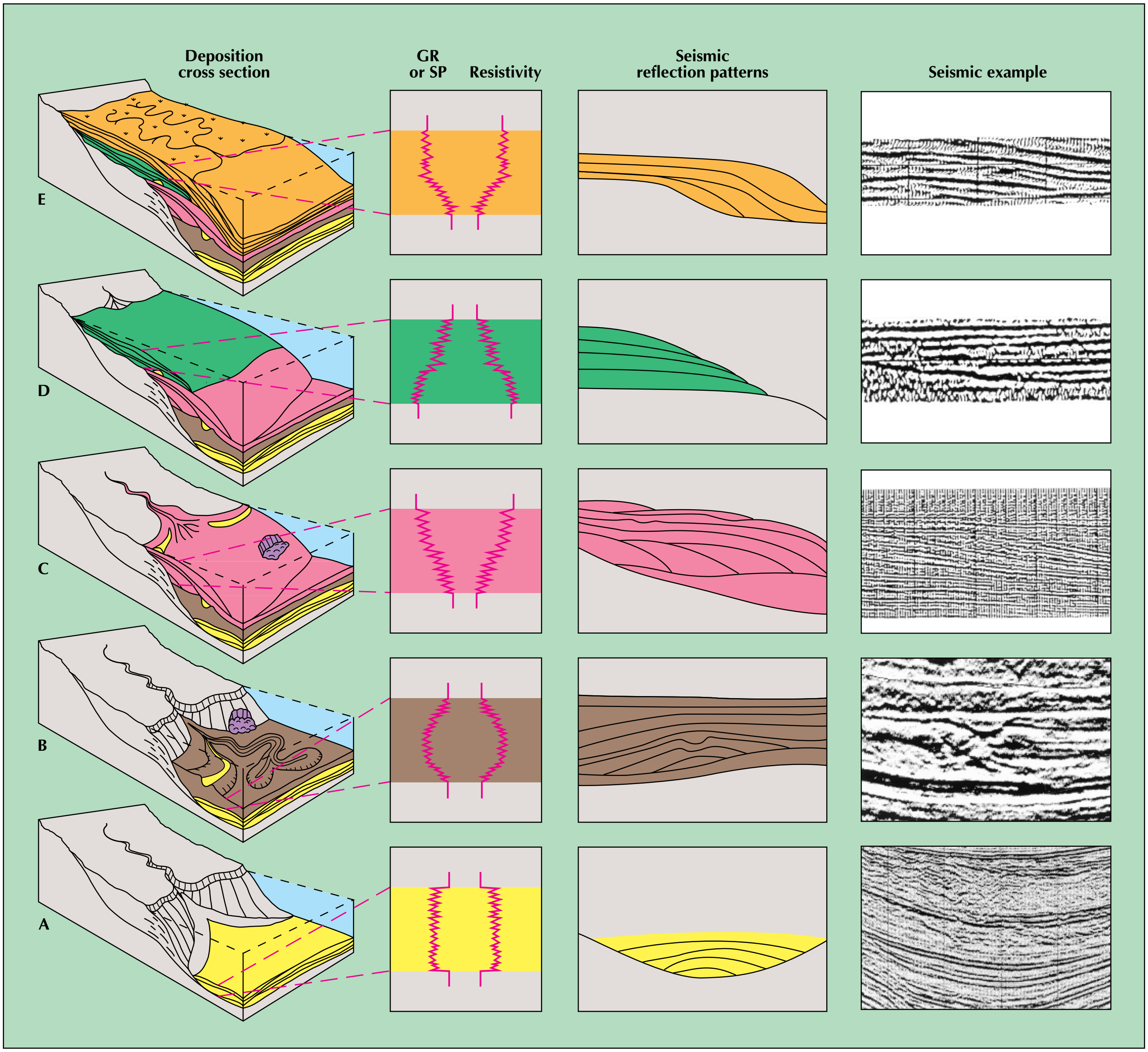
Starting with the lower lowstand systems tract at the bottom of a sequence, basin floor fans are typically isolated massive mounds of well-sorted grain flows or turbidite sands[1] derived from alluvial valleys or nearshore sands (next page, "A"). Log responses are blocky, with a sharp top and bottom bracketing clean sand. Seismic reflections curve down and terminate on the underlying sequence boundary—a feature called downlap—while the top may form a mound. The lowstand facies makes an excellent reservoir, with porosity often over 30% and permeability of several darcies.[2] It may be overlain by a thin clay-rich layer that can act as a seal, but more often it is overlain directly by the next depositional unit. In these cases, the basin floor fan acts as a hydrocarbon migration pathway. Fossil content is minimal, since deposition rates are often very high. Basin floor fans derive their hydrocarbon from previous sequences.

In areas of high deposition rate, the major component of the lower lowstand systems tract is the slope fan complex. Slope fans can be extensive and can exhibit several depositional styles, depending on the vertical gradient of the slope face and on the sediment source (next page, "B"). The complex may include submarine channels with levees, overbank deposits, slumps and chaotic flows. Log responses commonly are crescent shaped. A sharp base within the crescent commonly indicates sand in a channel, with a bell shape indicating fining upward as the channel is abandoned. On the other hand, channels may fill with mud. On seismic sections, leveed channels in the fan show a characteristic mound with a slight depression in the top. Sand-filled channels make excellent exploration targets, but may be difficult to track.[3] Sands flowing over channel levees may be deposited as overbank sheets and alternate with shales, creating subparallel reflectors. Such sands can provide stacked reservoirs with porosities of 10 to 30%, but are usually very thin. Slumps from shelf edge deltas create a chaotic or jumbled pattern—"hummocky" in interpreter's vernacular—easily identifiable on seismic data. Hydrocarbon sources for channel and overbank reservoirs are deeper sequences. Seals are provided by a widespread "condensed" section of shale, a thin layer representing prolonged deposition at very low rates that comes with the rise in sea level. The sealing shale also contains abundant marine fossils used for dating.

Part of the upper lowstand, the prograding wedge complex derives its name from shallowing-upward deltas that build basinward from the shelf edge and pinch out landward at the preceding shoreline (next page, "C"). Log response shows more sand higher in the section and less sand basinward, indicating a coarsening upward. The seismic signature shows moderate- to high-amplitude continuous reflectors that downlap onto the basin floor. This depositional unit often contains ample sand, especially near the sediment source. Updip seals are typically poor, however, and structural trapping is required for hydrocarbon accumulation.

The transgressive systems tract represents sedimentation during a rapid rise in sea level (next page, "D"). The shoreline retreats landward, depriving the basin of sediment. SP and gamma ray logs show a fining upward. Retreat of the shoreline gives rise to seismic patterns that appear to truncate basinward. In practice, this systems tract is commonly thin, and such patterns are usually imperceptible on typical seismic sections. Basal transgressive sands derived from reworked lowstand sands can be excellent reservoirs, except where shell fragments may later cement the sands. Shoreface sands will follow strike-oriented trends.

The top of the transgressive systems tract is the limit of marine invasion, and is called the maximum flooding surface. Widespread shale deposition results in a condensed section. Abundant fossils provide ages and well ties across the seismic section. This clay-rich layer shows low resistivity and high gamma ray readings. The seismic pattern of this surface is downlap, which becomes conformal—parallels adjacent reflectors—basinward, and disappears above the shelf. This surface is usually a very continuous reflector. At the shelf edge, it can commonly be identified by changes in reflection patterns above and below.



□*Components of sequences, their log responses, and predicted and observed seismic reflection patterns.*

Layers deposited during highest relative sea level are known as the highstand systems tract (above, "E")**. Early highstand sediments are usually shaly. The late highstand complex, deposited as the rise in sea level slows, contains silts and sands. Some late highstand sediments are deposited in the open air as fluvial deposits. Gamma ray and SP responses show a gradual decrease in gamma ray, indicating coarsening upward associated with decreasing water depth. Seismic reflections are characterized by sigmoidal—S-shaped—stratal patterns, similar to prograding wedge reflections. There may be deltaic and shoreface sands at the top of the section, but in general, this systems tract has poor reservoir sands, and updip seals are uncommon. Fossil abundances diminish as the marine environment becomes restricted to the deeper parts of the shelf.**

1. A turbidite is a rock deposited from sediment-laden water moving swiftly down a subaqueous slope.
2. Sangree JB, Vail PR and Sneider RM: "Evolution of Facies Interpretation of the Shelf-Slope: Application of the New Eustatic Framework to the Gulf of Mexico," paper OTC 5695, presented at the 20th Annual Offshore Technology Conference Proceedings, Houston, Texas, USA, May 2-5, 1988.
3. Sometimes channels can be seen in slices of 3D seismic volumes, but sequence stratigraphic studies are not commonly done on 3D data. An exception is the study described on page 62.

Components of a sequence may be repeated or missing, depending on local conditions and the rate of sea level change, but the basic sequence structure is predictable. Computer-generated models of sequence cycles are used to show the effects of sea level change, sediment supply and depositional profile (*below*).[10] These inputs can be varied to test their relative importance, or to produce stacks of sequences in an attempt to match real data.

Searching for Sand—A Case Study

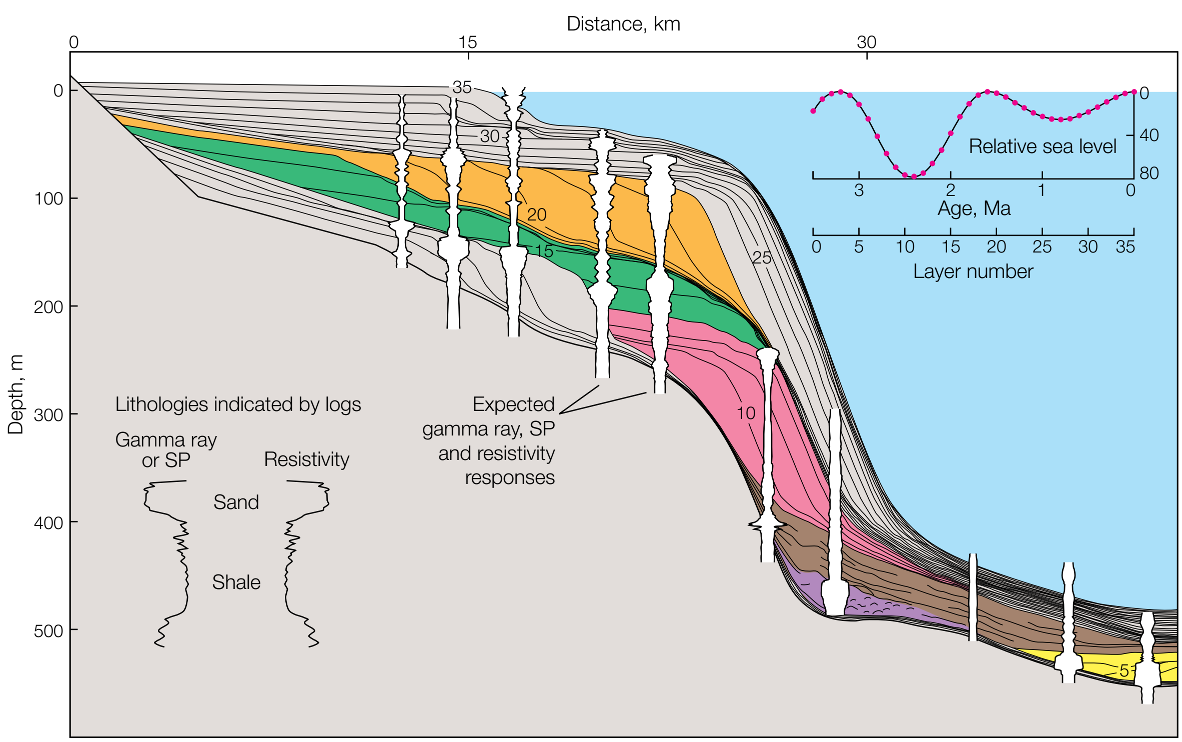
Sequence stratigraphy was applied in 1992 in the East Breaks area, offshore Texas (*next page, top*). Data included a two-dimensional (2D) seismic line and logs from seven wells. The seismic line was processed for structural imaging (see "Structural Imaging: Toward a Sharper Subsurface View," *page 28*) and the structural interpretation used four other lines to view the basin as a whole (see "Going for the Play: Structural Interpretation in Offshore Congo," *page 14*). In this case, the big picture shows a basin controlled by normal faulting to the north, which was the direction of the sediment source. Layers dip and thicken to the south.

Initially, seismic data and logs were interpreted independently to identify sequences and their bounding unconformities. Log-derived boundaries were compared with those from seismic data and the interpretation refined iteratively. Detailed seismic interpretation began with the most easily interpreted reflection patterns, and was pieced together—working upward, downward and back toward the wells—respecting the stratigraphy suggested by the sequence model.

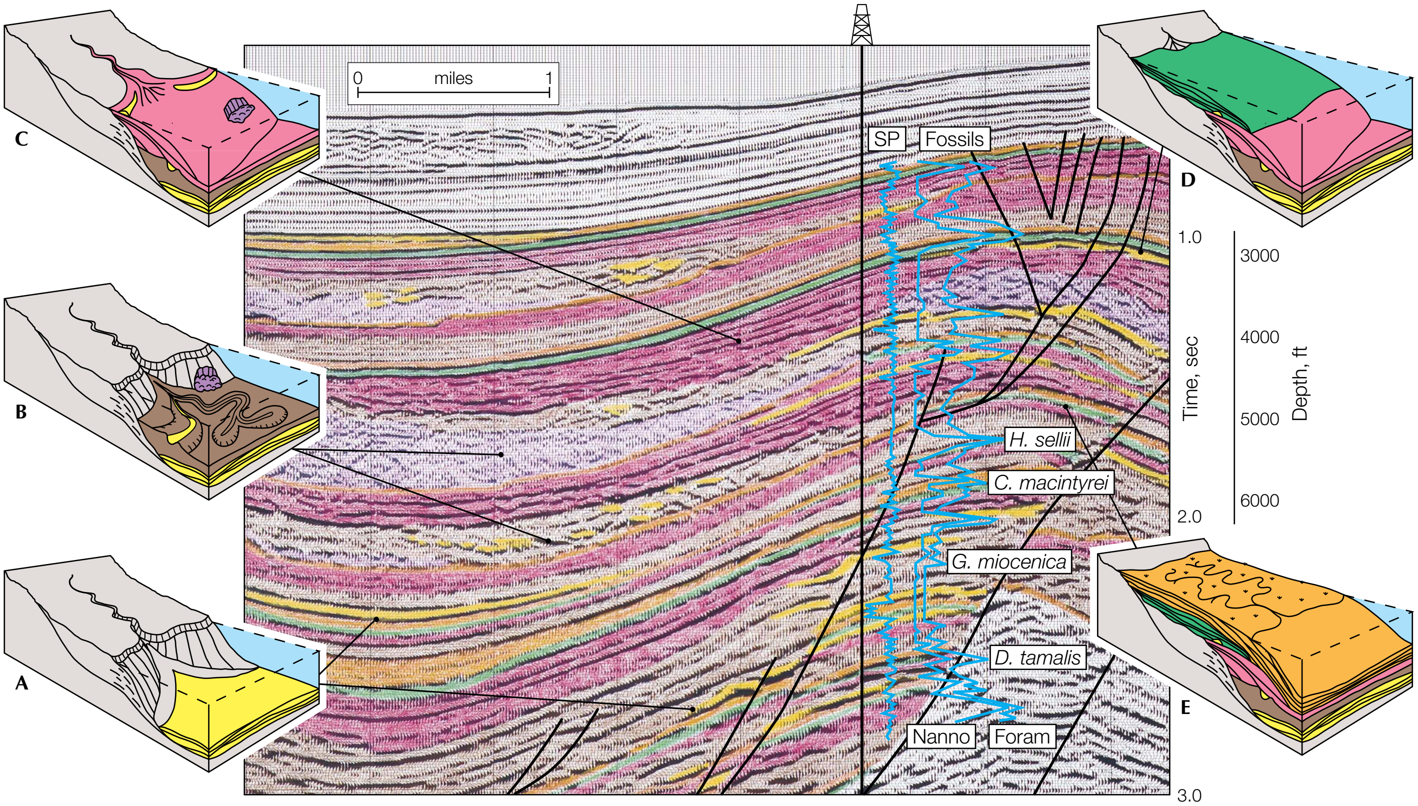
Logs from wells on the seismic lines were converted from depth to time using the nearest check shot—here, 3 miles [4.8 km] away.[11] Sands interpreted on spontaneous potential, gamma ray and resistivity logs were associated with seismic reflections at the well and tracked along the seismic section. Shales indicated by logs were noted for correlation with fossil data from cuttings.

Next was integration of biostratigraphy.[12] Fossils from cuttings help identify and date boundaries of each rock sequence. Fossil diversity and abundance are measured versus depth, which is converted to seismic travel time for easy comparison with the seismic section. Fossils of planktonic (floating) organisms are more widespread than those of benthic (bottom-dwelling) organisms and are therefore more useful in establishing regional time correlations. However, in shallow-water environments, benthic fossils are used because nearshore conditions may be too variable for planktonic fossils.

Fossils are also indicators of relative sea level. High fossil counts, or peaks, are associated with shales deposited during low sedimentation. Such conditions occur in the basin during time of high relative sea level, but also in deep water between fan deposits and outbuilding delta deposits (*page 58, top*). Two shale sections are expected within each sequence, one at the top of the slope fan and the other at the maximum flooding surface, associated with the furthest landward position of the shoreline. Biostratigraphy also holds the key to paleobathymetry—a measure of topography of the ancient ocean floor—needed to interpret



Sequences simulated using Scott Bowman's technique, showing all the components on page 53. Inputs are initial basin shape, sedimentation rate and relative sea level. Geologic time lines are numbered from 5 to 35, oldest to youngest. The sequence begins at 5. Expected log responses are plotted at ten locations. The left curve is SP or gamma ray, the right curve resistivity.



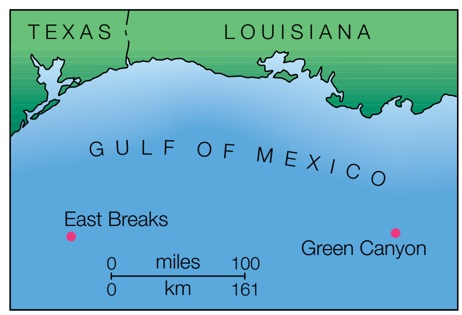
East Breaks, offshore Texas, seismic line with sequence components interpreted in color, SP log and fossil abundance curves. Block diagrams from page 53 point to representative examples on the section. This seismic section has nine sequences. Sequence components shown are not necessarily from the same sequence, which is why D appears stratigraphically above E.

the depositional environment. Paleodepth is derived from benthic fossils with known depth habitats (*next page top, right curve*). Knowing water depth helps to interpret deep or shallow water rock types and expected layer thicknesses.

Once seismic, log and biostratigraphic data are combined, a final, color-coded interpreted section is made. Very high amplitude reflections may be highlighted with hatching. These so-called bright spots are analyzed for anomalies in amplitude variation with offset associated with hydrocarbons (see "Hydrocarbon Detection With AVO," *page 42*). In the East Breaks example, the most promising prospect is a large, sandy basin floor fan. Shales interpreted above and below could provide seal and source rock, respectively.

Overcoming Limitations of Sequence Stratigraphy

Sequence stratigraphy has proven useful for petroleum exploration, but it is commonly misapplied.[13] There is controversy over whether the technique can be applied to carbonate systems since it was designed to explain sand-shale systems. Some experts maintain that sequence stratigraphy is easier in carbonates because carbonates are extremely sensitive to sea level change.[14] There is unanimous agreement, however, that low sedimentation rates often pose special problems. When sedimentation rate is moderate to high, layers within a sequence are tens to hundreds of meters thick, comfortably within the resolving power of a typical seismic wave (*next page, bottom*). But when sedimentation rate is low, several sequences might fit within a seismic wavelength. Sequence stratigraphy cannot be confidently applied here, but it has been done countless times. A useful interpretation in thinly-bedded regions requires abandon-



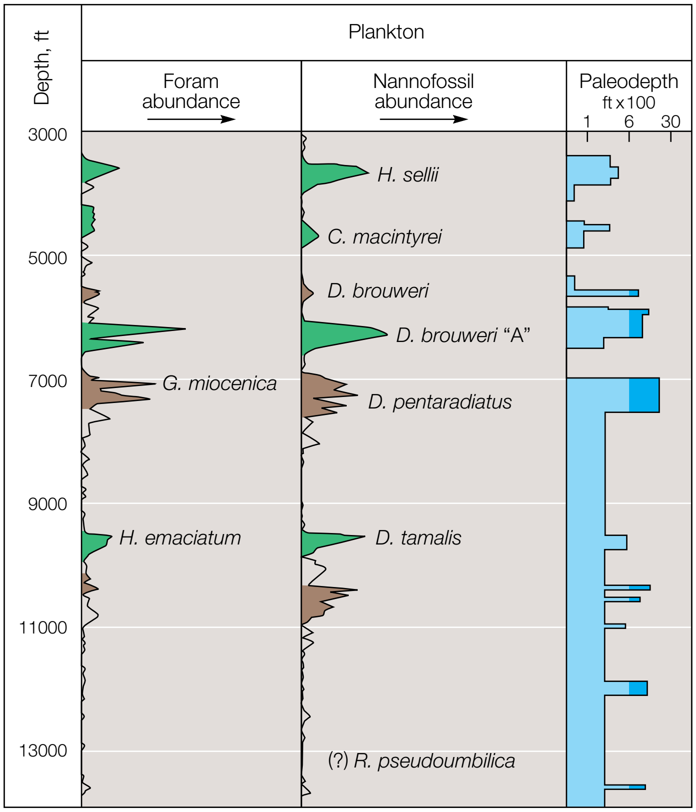
10. Bowman SA and Vail PR: "Computer Simulation of Stratigraphy," *American Association of Petroleum Geologists Bulletin* (1993): in preparation.

11. A check shot is a wireline survey that checks the seismic travel time from the surface to a chosen depth in a well. Depths are chosen from logs. A geophone is conveyed by wireline to the desired depth and a seismic source is set off at the surface. The travel time is recorded and doubled to compare with the surface seismic travel time.

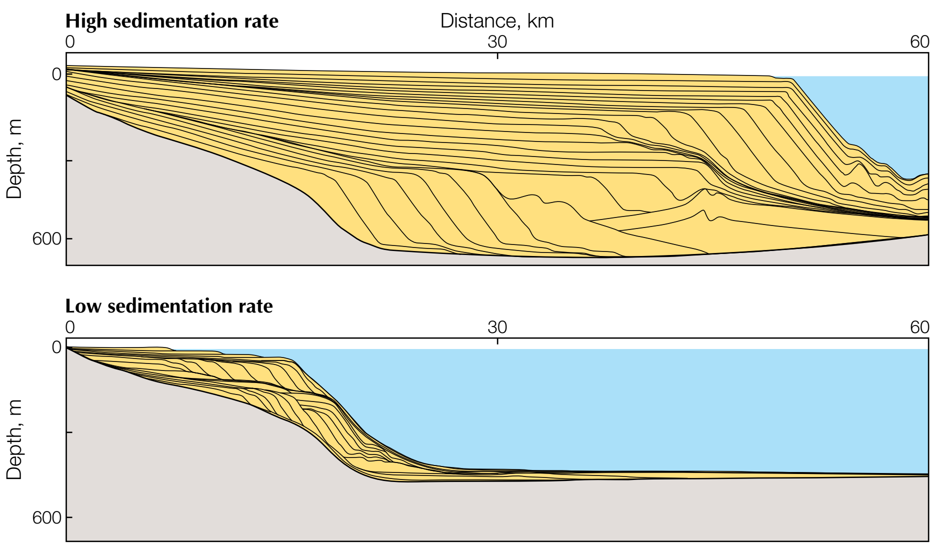
12. For an integrated biostratigraphic study:
Bell DG, Selnes H, Bjorøy M, Grogan P, Kilenyi T and Trayner P: "Better Prospect Evaluation with Organic Geochemistry, Biostratigraphy and Seismics," *Oilfield Review* 2, no. 1 (January 1990): 24-42.

13. Posamentier HW and James DP: "An Overview of Sequence Stratigraphic Concepts: Uses and Abuses," in Posamentier HW, Summerhayes CP, Haq BU and Allen GP (eds): *Stratigraphy and Facies Associations in a Sequence Stratigraphic Framework,* International Association of Sedimentologists Special Publication, 1992.

14. Vail P, Audemard F, Bowman SA, Eisner PN and Perez-Cruz C: "The Stratigraphic Signatures of Tectonics, Eustasy and Sedimentology—An Overview," in Einsele G et al. (eds): *Cycles and Events in Stratigraphy.* Berlin, Germany: Springer-Verlag (1991): 617-659.



Typical Gulf of Mexico fossil abundance peaks and paleodepth curve. Fossil abundance curves based on analysis of cuttings for foraminifera—protozoa with calcareous external skeletons—and nannofossils, a broad category of extremely small, usually algal fossils. Peaks indicate the presence of shales at the top of the slope fan complex *(brown)* ***and at maximum sea level*** *(green)*. ***The right curve indicates fossil habitat depth, in which dark blue is deep water and light blue is shallower.***



High *(top)* ***and low*** *(bottom)* ***sedimentation rates, shown on synthetic sequences. The basic shape of each layer follows the initial basin shape, but layer thickness varies with sedimentation rate. Only thick layers can be resolved with seismic methods.***

ing small-scale features and concentrating on larger scale, longer term processes that control the generation of sequences.

With this in mind, Vail and coworkers proposed a hierarchy of stratigraphic cycles based on duration and amount of sea level change.[14] Duval and Cramez at TOTAL Exploration worked with Vail to provide subsurface examples and to expand the application to hydrocarbon exploration.[15] The hierarchy assigns frequencies to the mechanisms of eustasy enumerated by Fairbridge (*page 52*), viewed in light of plate tectonics (*next page, top*). The first-order cycle, which is the longest, tracks creation of new shorelines resulting from the breakup of the continents. Although this breakup does not follow a cycle, it has happened twice, with a duration of over 50 million years. The second-order cycle is landward and basinward oscillation of the shoreline that lasts 3 to 50 million years. This oscillation is produced by changes in the rate of tectonic subsidence and uplift, caused by changes in rates of plate motion. Both first- and second-order cycles may cause changes in the volume of the ocean basins resulting in long-term variations in global sea level. The third-order cycle is the sequence cycle, lasting 0.5 to 3 million years. Fourth- and higher order cycles may be correlated with periodic climatic changes.

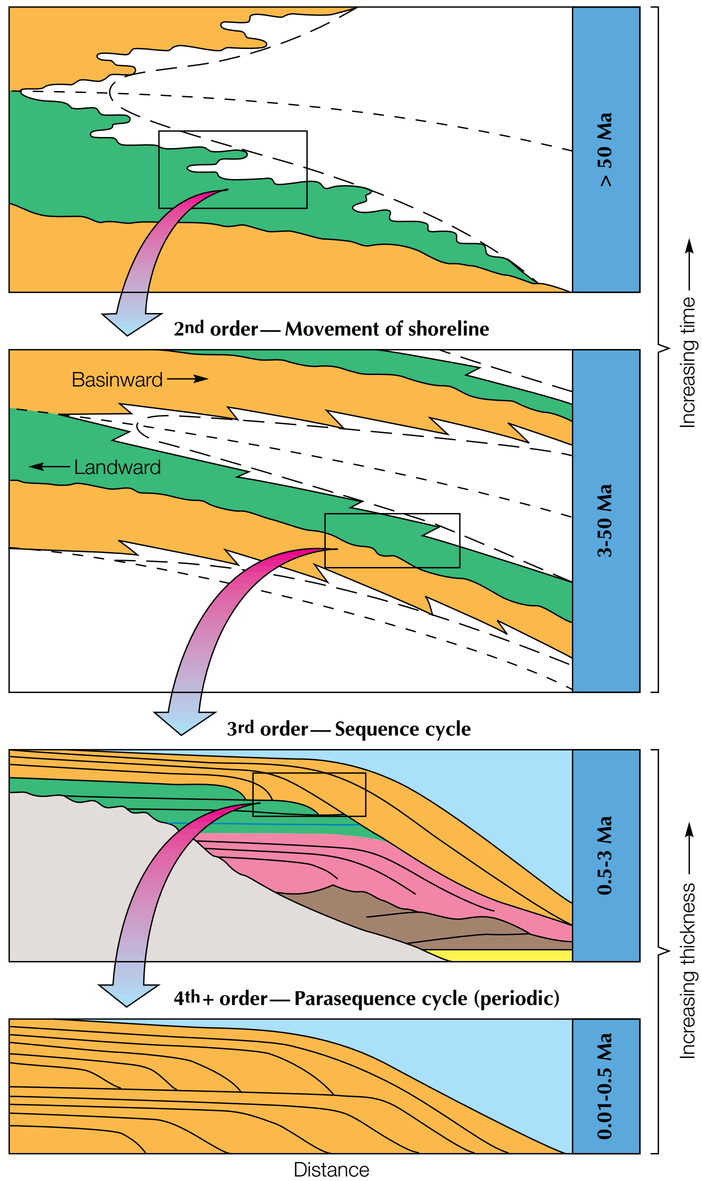
The following example, with its low deposition rate, approaches the limit of interpretation in terms of third-order cycles. It comes from the Outer Moray Firth basin in the UK sector of the North Sea, where the initial basin shape, tectonic activity and variation in the rate of deposition add a twist to the interpretation (*pages 60-61*).

Stratigraphic interpretation of the last 65 million years of sediments in the Outer Moray Firth is more difficult than in the Gulf of Mexico because slower deposition in the Central North Sea resulted in thinner units, many of which cannot be resolved by seismic waves. During this period, the Outer Moray Firth has 17 sequences totaling 5000 feet [1524 meters] of sediments (*pages 60-61, middle and bottom*), compared to the Gulf Coast, with 10 sequences totaling 9000 ft [2750 m]. In the North Sea, however, depositional processes juxtaposed a variety of lithologies, providing reliable calibration points for accurate conversion of logs from depth to time using synthetic seismograms (*right, bottom*). In the Gulf of Mexico, this conversion is typically done with only nearby checkshots; sands and shales commonly show periodic alternation with depth at wavelengths that make comparisons between seismic sections and synthetic seismograms nonunique.

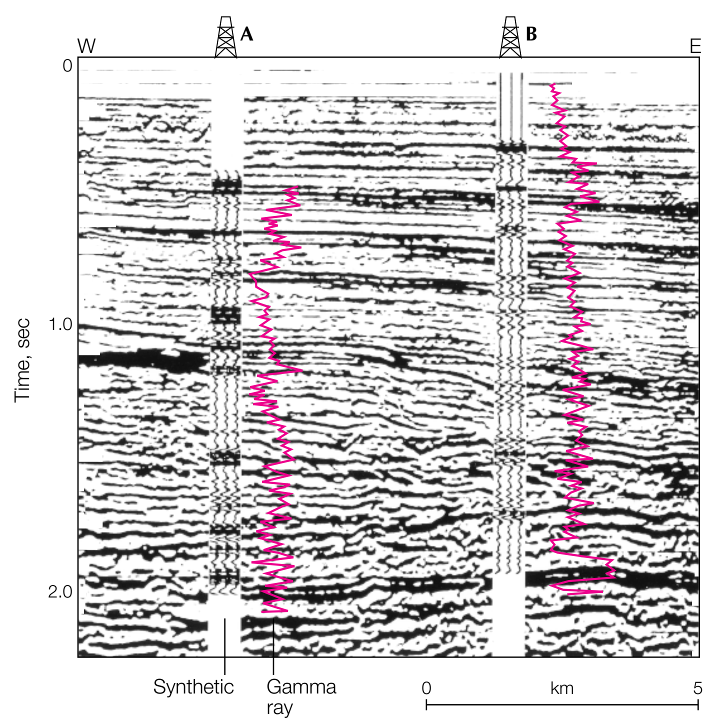
Stratigraphic study is always preceded by structural interpretation. In addition, a paleogeographic interpretation of the Outer Moray Firth shows that late in the Cretaceous period—when the sequences under study began to be deposited—a smooth basin floor sloped gently from northwest to southeast. During a relative fall in sea level, sediments were deposited as slope fans. Their seismic expressions indicate lobes with channels and some chaotic flows—large-scale slumps with jumbled seismic character. As sea level rose, a wedge of outbuilding deltas was deposited. Sea level maximum is associated with a depositional hiatus, shown only as a thin line. Deposits synchronous with this surface may be found on what is now land in Europe, but in the basin, sediments that correspond to periods of high relative sea level are rare.

Why are elements of the classic Vail model missing from this sequences in this basin? One explanation is the competing influences of tectonic uplift and sea level change. As global sea level rose and fell, continual regional uplift kept the sea from reaching levels high enough to allow formation of units typical of high relative sea level. Only once, at the top of the third sequence, does a thin layer of high relative sea level sediments appear (orange). Another interpretation is that thin, high relative sea level sediments were deposited, but eroded, and so are not preserved in the section (*pages 60-61, bottom*).

15. Duval B, Cramez C and Vail P: "Types & Hierarchy of Stratigraphic Cycles," presented at the International Symposium on Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, Dijon, France, May 18-20, 1992.



Hierarchy of cycles, decreasing downward in the duration of sea level change and in area of influence. At the top, the first-order cycle lasts at least 50 million years and is caused by major changes in the configuration of tectonic plates. The second-order cycle, lasting 3 to 50 million years, is also controlled by plate motion. It involves movement of the shoreline landward and basinward, on the scale of continents. The white area shows the time in which there is no rock record, usually due to lack of depostition. The third-order cycle, of 500,000 to 3 million years, is the sequence cycle described in the main text. It is caused by long-term tectonic activity and short-term global sea level changes. Fourth- and higher order cycles, of 10,000 to 500,000 years, are of shortest duration. They are driven by sea level changes caused by periodic climatic variation. Cycles of this order are called parasequence cycles.



Synthetic seismograms and gamma ray logs from two wells tying with the Outer Moray Firth seismic line. Synthetics, based on sonic and density logs, provide a depth-to-time correlation for integration of log, paleo and seismic data.
(Courtesy of Amoco UK.)

This section can also be interpreted in terms of second-order cycles (*page 62, top*). The entire set of 17 depositional sequences can be bracketed by five second-order cycles, based on physical stratigraphy and biostratigraphy. Major biostratigraphic gaps exist at the boundaries of each second-order cycle, and the boundaries can be seen to represent major changes in the depositional style of basin fill.

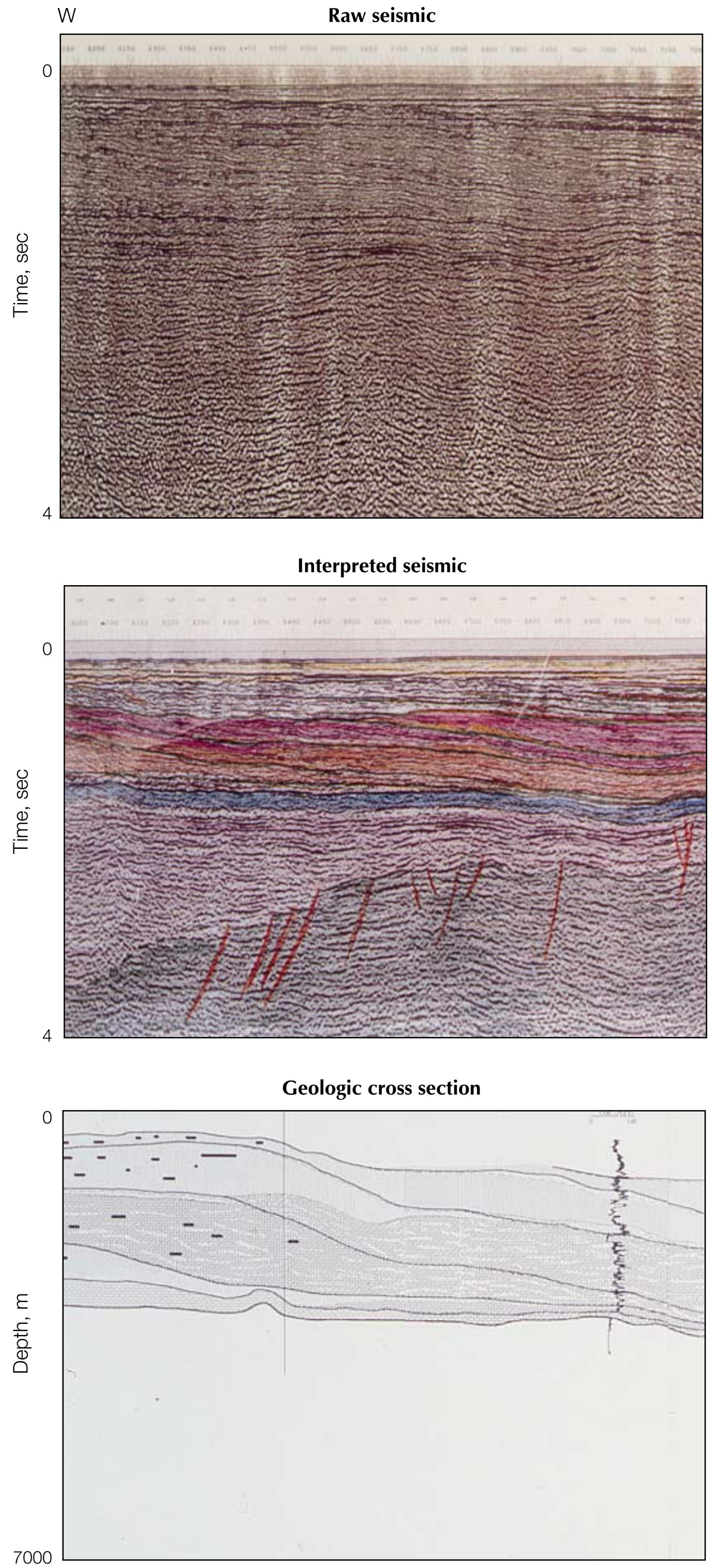
Studies in 3D

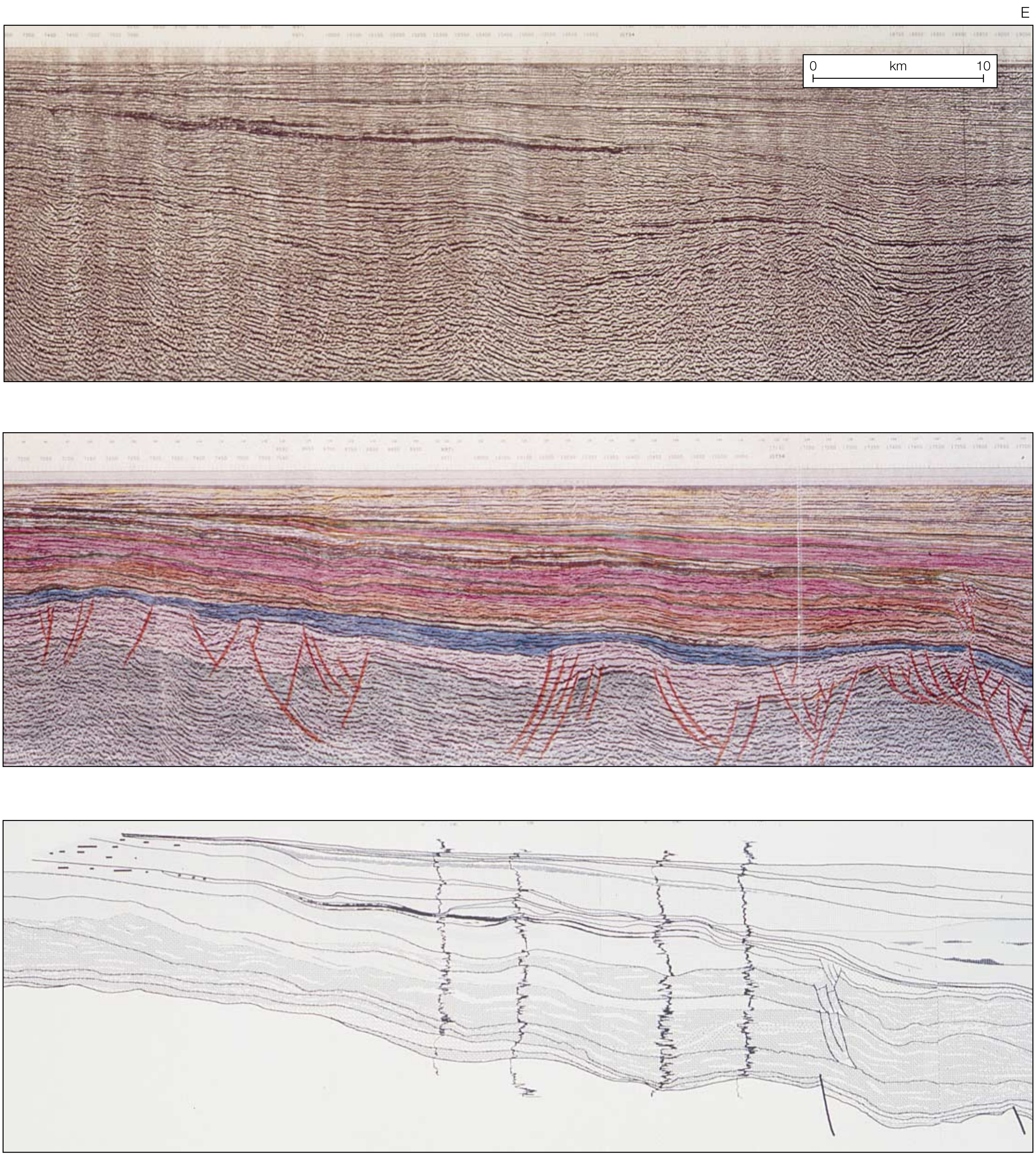
If the volume of earth in a study area is small enough, workstations can add a new dimension to sequence stratigraphy. In the Green Canyon area of the Gulf of Mexico, interpreters concentrated on a fan deposited in a syncline on the continental slope 1 to 2 million years ago. Regional sequence stratigraphy was established using 2D seismic data and paleontologic control from six nearby wells. Zooming in on a subset of this data, interpreters assembled a series of 2D panels for 3D interpretation.

The top and base of the slope fan were interpreted over a six-block area (54 square miles [138 km^2]). The thickest part of the slope fan coincides with the stacked channels that carried shallow-water shelf and delta sands into deep water, greater than 200 m [656 ft] (*page 62, middle*). A series of stacked channels, possibly filled with sand, is visible within the slope fan interval.

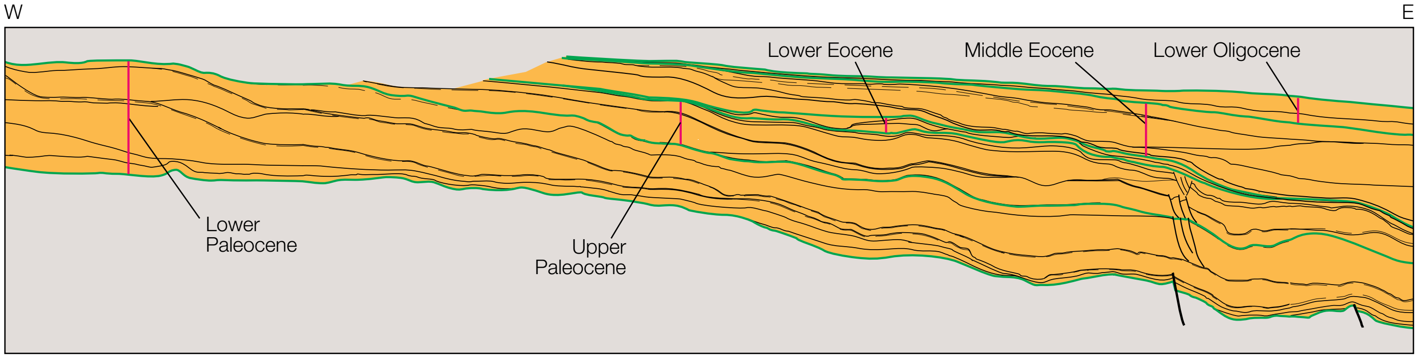
The goal of this interpretation is to identify exploration targets. Although lithology of the channel deposits is difficult to identify in the horizon slice, geology predicts that the channel will terminate in a sand-rich fan.[16] The channel was tracked south, and a fan was discovered in the next block of seismic data.

16. A horizon is the surface separating two rock layers. In seismic data, a horizon shows up as a reflection. A reflection tracked in a 3D cube of seismic data and displayed in plan view is called a horizon slice. Depths or times to the reflection are contoured or color-coded.

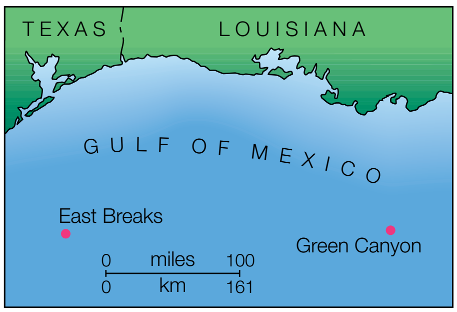




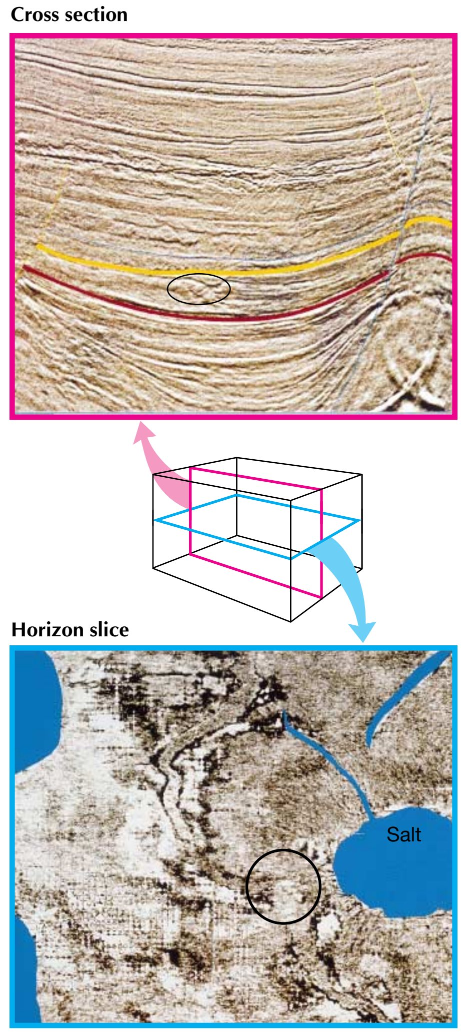
Comparison of seismic and log data from the Moray Firth, North Sea, including the original seismic line (top)*, the interpreted line* (middle) *and the geologic cross section with gamma ray logs. Permian and Carboniferous basement* (green) *are followed by Jurassic to Lower Cretaceous sediments* (purple)*. Both show evidence of rifting during and after deposition. In the Upper Cretaceous, chalk* (blue) *filled the earlier rifts. The chalk was deposited in open marine conditions, with no land exposed nearby. On the left* (west) *edge, a Paleocene (Danian) chalk debris flow appears as a chaotic zone on top of the earlier chalk. Basin relief was minimal and sea level was high at the onset of the first sequence in the Tertiary. Low relative sea level deposits—slope fans and chaotic flows—are brown (color convention is the same as in the Gulf of Mexico example). River deltas building out during low relative sea level are pink. Sea level maxima appear as thin green lines.*



□***Outer Moray Firth data reinterpreted in terms of second-order cycles. Basinward movement of the shoreline is orange and landward movement is green. Colors correspond to second-order cycles*** *(page 59, top).*



□***Seismic line and horizon slice from a cube of 3D data in Green Canyon, offshore Louisiana. The top*** *(yellow line)* ***and bottom*** *(red)* ***of a slope fan were interpreted using sequence stratigraphy. A stack of submarine channels can be seen in the seismic line*** *(oval).* ***Normally, channels like these would be difficult to track, but in 3D the task is simple. The 3D data can be flattened at the top of the fan, and sliced horizontally to reveal a map*** *(bottom).* ***Here, the channel can be seen to meander from north to south around an emerging salt dome. A slump off the flank of the salt*** *(circle)* ***has fallen into the channel. This channel was tracked to the next block south, where it terminated in a slope fan lobe, predicted to be sandy.***



Frontiers

Sequence stratigraphy continues to evolve. One area of investigation is high-resolution sequence stratigraphy, which is performed at a higher resolution than seismic wavelengths, usually with log and outcrop studies. ARCO, TOTAL and Esso scientists performed a very high-resolution sequence stratigraphy study on a roadside ditch, which served as an analog of an incised valley and delta system. The system measured only 50 cm [20 in.] from bottom to top but obeyed the same physical laws as systems hundreds of meters thick.[17]

Sequence stratigraphy is achieving some success in areas where it was not designed to work. Studies in carbonates show that although the depositional layering patterns are different from sand-shale systems, the technique has the power to explain and predict sediment distribution and lithologic content.[18] Sequence stratigraphy has also been applied with success to nonmarine deposits in continental basins and in marine basins isolated from continental sediments.

Sequence stratigraphy, as proposed by the Exxon group, is not without controversy. Some alternative schemes to explain sequences place more emphasis on sediment supply[19] or tectonic activity.[20] Whatever their area of expertise, stratigraphers agree on the main problem in sequence stratigraphy—overextending the model to fit every study area. Bilal Haq, while at the National Science Foundation in the USA, compiled ten commandments for sequence stratigraphers[21] and Henry Posamentier of ARCO Oil and Gas Company has written on the uses and abuses of the technique.[13] They approach the subject from different perspectives, but their message is the same—where sequence stratigraphy works, use it; if it doesn't work, the problem is with the application, not the theory. —LS

17. Posamentier HW, Allen GP and James DP: "High Resolution Sequence Stratigraphy—The East Coulee Delta, Alberta," *Journal of Sedimentary Petrology* 62 (1992): 310-317.
18. Jacquin T, Garcia J-P, Ponsot C, Thierry J and Vail PR: "Séquences de Dépôt et Cycles Régressif/Transgressifs en Domaine Marin Carbonaté: Exemple du Dogger du Bassin de Paris," *Contes Rendues de l'Académie des Sciences de Paris* 315 (1992): 353-362.
19. Galloway WE: "Genetic Stratigraphic Sequences in Basin Analysis I: Architecture and Genesis of Flooding-Surface Bounded Depositional Units," *American Association of Petroleum Geologists Bulletin* 73, no. 2 (February 1989): 125-142.
20. Sloss LL: "Tectonics—The Primary Control on Sequence Stratigraphy: A Countervailing View," *Distinguished Lecture Tours Abstracts, American Association of Petroleum Geologists Bulletin* 74, no. 11 (November 1990): 1774.
21. Hag BU: "Ten Commandments for Sequence Stratigraphers," presented at the International Symposium on Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, Dijon, France, May 18-20, 1992.