Predictability of the Stratigraphic Record from the Outcrop to Multiple Seismic Attributes–Past, Present, Future

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Over the last 50 years, the introduction of the seismic tool and depositional sequence concepts derived from it have revolutionized the way sedimentary geologists view strati-graphy. The fundamental driving principles of sequence stratigraphy are, however, grounded in observations from the outcrop. Most importantly, they derive from (1) Sloss’s recognition of large-scale continent wide unconformities that serve to divide sedimentary strata into sequences; and (2) the observations by Wheeler and Campbell that there are time-significant physical surfaces, at the bedset and larger scale, that are correlative over broad regions. Facies are then interpreted within this physical stratigraphic framework. Vail recognized that seismic reflections follow these correlative surfaces in the rocks and are not the massive time transgressive formational boundaries. Utilizing discontinuities as a basis for packaging sedimentary rocks, the stratigraphic record can be divided into a series of depositional sequences that contain a repeated pattern of lithofacies.

Furthermore, it appears that even though basins record their own tectonic history, similar-aged sequences are present in different basins around the globe. This has led to the hypothesis that depositional sequences are sea level driven and globally synchronous. Results from the current Ocean Drilling Program suggest that there is global synchronicity for Neogene-aged sequences, and the new Drilling Program, set to commence in 2005, will have riser capability and will continue to provide a rigorous test of the Vail global sea level hypothesis.

Over the last 20 years, new outcrop analysis and the introduction of numerical sedimentary modeling have further developed and enhanced the original seismic stratigraphic concepts. Using numerical modeling, Jervey and Vail derived the accommodation concept, which predicts that the first-order controls on stratigraphy are subsidence, sea level, and sediment supply. A new generation of outcrop study has used seismic-scale exposures to describe stratigraphic architecture and lithofacies relationships in classic areas like the Guadalupe Mountains, the Western Interior of the United States, and the Pyrenees and the Dolomites of Western Europe. Physical criteria are well established for the recognition of sequence boundaries and the distinguishing characteristics of sequences in both siliciclastic and carbonate terrains.

The recognition of repeated and predictive stratigraphic patterns has emerged from the sum of this global research effort. Siliciclastic and carbonate depositional sequences, for example, can be partitioned into linked contemporaneous depositional systems or systems tracts. For siliciclastics and in mixed carbonate/clastic sequences, a basin restricted or lowstand systems tract is, in many places, characterized by thick wedges of gravity-flow dominated sediments, deposited during times of sediment bypass across the shelf and fed by incised river or shelf-edge-restricted deltas. Diminished in-situ carbonate bank and platform growth may occur if oceanographic conditions conducive to organic productivity persist in downslope positions. Mid-sequence, organic-rich, clay or carbonate-prone condensed sections overlie these deposits and are correlative updip to retrogradational transgressive sandstones or grainstone shoals (i.e., transgressive systems tract). Thick aggrading to prograding highstand carbonate platforms, or siliciclastic deltas and shoreline deposits downlap the transgressive systems.

Sediment supply and type, basin margin relief, and slope declivity all play major roles in controlling sequence architecture. Sequences often depart from the published Vail model, mostly because of differences within their lowstand systems tracts. Lowstand geometries can include lower slope and basin floor deposits that are physically separated from a prograding shelf-edge complex. Alternatively, the prograding shelf-edge complex can directly overlay the slope and basin floor deposits. In all cases, two bypass surfaces may form in association with the lowstand system. The first is a basinward dipping surface onlapped by the slope and basin floor deposits. The second is a more horizontal surface of bypass/erosion within the prograding complex. When both are present, the two surfaces have engendered debate over where to place the sequence boundary. Using the approach of Mitchum, the first surface is the type I sequence boundary, because it is onlapped by basin-restricted sediments deposited during base level fall and lowstand. The upper surface is an intra-lowstand bypass surface. It forms within the prograding complex of the lowstand systems tract when sediments infill the accommodation space immediately basinward of the previous highstand depositional-shelf edge.

This has been demonstrated by new experimental work at St. Anthony Falls Laboratory of the University of Minnesota where stratigraphy was formed in a tank under controlled rates of sediment supply, subsidence, and base-level change. During a rapid fall in base level, significant sediment loading destabilized the stratigraphy, triggering major growth faulting and the transfer of a significant volume of sediment into the deeper part of the tank. This fill then formed the undercarriage for a well-developed prograding complex, which in the latter stages of the fall advanced from the mouth of an incised valley and infilled the remaining accommodation space. As it prograded during the fall, the top of this complex was eroded. Then, as base level turned and started to rise, erosion ceased and the prograding complex began to aggrade, leading to depositional onlap back across the surface of erosion and its preservation within the lowstand systems tract. Consequently, the intra-lowstand bypass surface is significant in that it records the erosional regression of the shoreline within the lowstand system during a relative fall in sea level. Furthermore, it is related to the sequence boundary in that the two merge at or landward of the former highstand depositional-shelf edge.

Natural examples of lowstand systems tracts containing well-developed, extensive intra-lowstand bypass surfaces include the Brushy Canyon Formation in the Permian basin (USA), and the Miocene strata preserved beneath the Niger and New Jersey continental shelves. Like the experimental stratigraphy, these strata formed along basin margins having relatively low relief and high sediment supply. At the other end of the spectrum are basin margins with high relief and sediment supplies too low to infill the accommodation space seaward of the depositional-shelf edge. These margins are characterized by small prograding complexes perched on the uppermost slope and detached from deeper deposits on the lower slope and basin floor by slumps, slide scars, and submarine canyons.

Examples include the Pliocene–Pleistocene strata along the Gulf of Mexico and New Jersey continental slopes (USA), as well as the Paleogene sequences of the North Sea.

In addition to sediment supply and relief, the basin margin slope also affects type I lowstand geometries. The Gulf of Mexico and New Jersey Pliocene–Pleistocene margins, as well as the Paleogene North Sea margin are steep, which appears to have contributed to their prograding complexes being small and perched. In contrast, the ramp settings prevalent in the middle Cretaceous of the Western Interior of North America have low relief and a low slope. Along these margins, type I lowstand systems tracts with extensive intra-lowstand bypass surfaces are common. This is because the low dip of the ramps significantly limited the accommodation space immediately seaward of the depositional-shelf edge, and this space was often completely infilled with sediments before a relative fall in sea level had ended. This scenario was, in fact, reproduced during the formation of the experimental stratigraphy mentioned above, but over an earlier, slower change in base level.

Type I lowstand systems tracts thus span a continuum of geometries. At one end of the spectrum are relatively large prograding complexes that contain well-developed intra-lowstand bypass surfaces, and which step out basinward over lower slope and basin floor deposits. At the other end of the spectrum are relatively small prograding complexes that are perched on the uppermost slope and separated from lower slope and basin floor deposits by a mid-slope region of submarine canyons and slope failure. The principal variables that govern where along the spectrum a type I lowstand geometry will form are sediment supply, basin margin relief, and basin margin slope. The latter two variables constitute spatial variations in accommodation space, which are different from temporal variations caused by subsidence and sea level change.

These spatial factors are especially important in carbonate sequences where the organic growth potential of platforms can generate a range of depositional slopes from near vertical to ramps of less than 1°. The thickness and volume of carbonate lowstand systems are dependent on the existence of environmental conditions conducive to carbonate growth (i.e., carbonate “refugia”). Where slopes are steep, the “refugia” are limited and deposition is diminished. The lowstand is recorded in subaerial features on the shelf, erosion at the platform margin, and by deposition of debris wedges at the toe-of-slope and small in-situ carbonate banks perched at or below the platform edge. The isolated platforms of the Pleistocene of the Caribbean and the Miocene of Southeast Asia show this type of lowstand geometry. At the other end of the spectrum, low-angle depositional slopes provide the opportunity for larger, more widespread “refugia” and significant carbonate deposition. The Devonian of western Canada and the Permian of west Texas provide examples where significant downslope lowstand deposition occurs.

As the next decade begins and with the extension of petroleum exploration into the deep-water realm of the continental slope, major improvements in the seismic tool portend a bright future for sedimentary research. Stratigraphers, committed to an integrated use of technology, have an unprecedented array of tools at their disposal. The introduction of 3-D seismic, seismically-derived attributes (e.g., amplitude, frequency, phase), and visualization technology integrated with rock physics, core, and outcrop lithofacies dimensions provide the opportunity to delineate meter- to decimeter-scale stratigraphy. Attribute and seismic facies are mapped as 3-D volumes and give a detailed view of individual stratal bodies. This is especially dramatic in the Neogene-aged deep-water gravity flow deposits that have become the current focus for deep-water hydrocarbon exploration. Development of 2-D and 3-D numerical process-response models, physical sediment models, outcrop dimensional data, and forward seismic models help populate geometrically-constrained stratigraphic models, and validate seismic predictions of stratigraphy and lithofacies.