Guide to Sequence Stratigraphy

This guide is primarily aimed at the application of sequence stratigraphy to outcrops. As a result, none of the examples deal with topics related specifically to cores, well logs, or most significantly, seismic. Perhaps the best way to work through this guide is to start with accommodation and to continue down the list of topics from there. Many of the illustrations in this introduction to sequence stratigraphy are modified from the figures in Van Wagoner et al.'s Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops (AAPG Methods in Exploration #7).

Interested readers should study that reference and other references in the Further Reading section for a fuller explanation of the concepts introduced here.

Introduction

Stratigraphy

Stratigraphy is the study of the layered character of sedimentary rocks. Geologists use a variety of strategies to interpret the origin of these rocks and predict the extent of their lithofacies and rock character. Strategies mix sedimentological tools like: Stenos law that sediment accumulation is captured by the superposition of its layers; vertical stacking and lateral associations of lithology coupled to Walther's Law; biofacies identification (ichnofacies and fossils); sedimentary structures; sequence stratigraphy (a consideration of relationships to base level change and the production of erosional and depositional generated surfaces); chronostratigraphic markers (bio-stratigraphic, volcanic, magneto-stratigraphic, bio markers, radioactive markers or storm layers or sequence stratigraphic). None of these tools are used in isolation from one another. In fact the differences between many of these sub-disciplines of stratigraphy are 'fuzzy'. Sequence stratigraphy for instance carries not only the connotations related to the interpretation of the surfaces used to interpret the stratigraphic section but also a consideration of sedimentology and chronostratigraphy. However the bottom line is that most geologists want to determine the extent and origin of a lithofacies body, package or series of packages that concerns them and not how the tools they use are defined or fit preconceived classifications of the stratigraphic techniques being used. Just as an eater tends is not concerned by the number of prongs a "fork" should have so long as it conveys food to one's mouth so most stratigraphers do not care what obscure stratigraphic surfaces are called!

The interpretation of sedimentary sections and prediction of their facies heterogeneity's involves the analysis and integration of geometrically related data. It also involves the mental process of iteratively and successively back stripping the sediment in reverse order of accumulation. The reassembly tracks the evolution of the sedimentary system, its hydrodynamic setting, and accommodation. The genetic character of the sedimentary sequences, cycles, parasequences, and/or beds is determined by assuming that they are the products of changes in accommodation as the sediment is reassembled. The limits to this analytical strategy are tied to knowledge of the inferred depositional setting while the advantage is that it formulates new questions that lead to more realistic interpretations and enhanced predictions of lithofacies heterogeneity's.

Sequence Stratigraphy

Stratigraphic interpretations explain how sedimentary rocks acquire their layered character, lithology, texture, faunal associations and other properties. The analysis of these properties can be used to explain how the mechanisms of sediment accumulation, erosion and inter-related processes produced the current configuration of these rocks.The sequence stratigraphic approach recommended on this web site for the interpretation of sedimentary rocks contrasts with Lithostratigraphic analysis which maps lithofacies independent of subdividing external and internal boundaries or Allostratigraphic analysis that uses bounding discontinuities including erosion surfaces, marine flooding surfaces, tuffs, tempestite, and/or turbidite boundaries etc. as time markers independent of any model of base level change. Sequence Stratigraphy analysis applies allostratigraphic models to interpret the depositional origin of these sedimentary strata and while assuming, though this is not always stated, an implicit connection to base level change. It does this by establishing how the sequence of strata accumulated in order in the sedimentary section over a subdividing framework of surfaces. The major bounding and subdividing surfaces of this template are commonly represented by:

- Maximum Flooding Surfaces (mfs)
- Transgressive Surfaces (TS)
- Sequence Boundaries (SB)

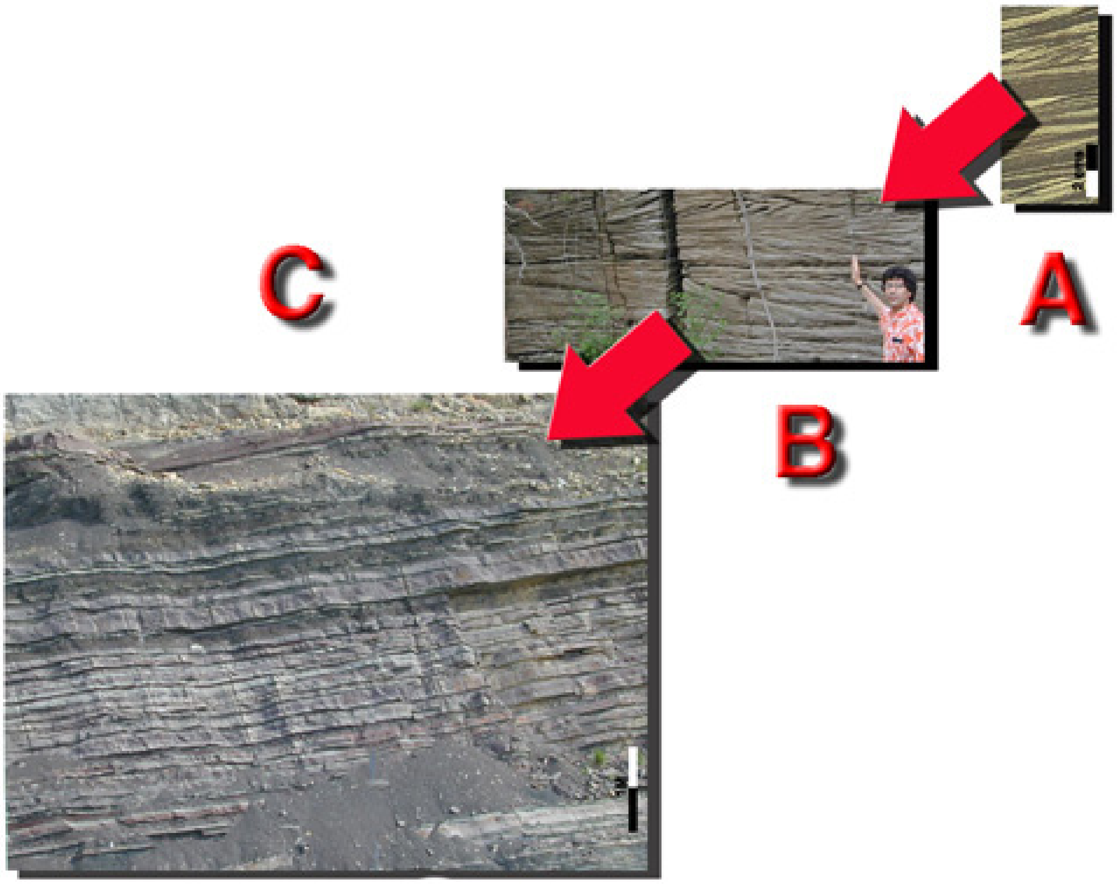
This subdivision of the sedimentary section provides the order in which the sediments were laid down (the law of superposition of Steno), and so their relative age. The arrangment of the vertical succession of facies of the sediment geometries bounded by the surfaces, stacking patterns, forms a major element to the interpretation of the depositional settings of stratigraphic section. These stacking patterns vary between:

- Unconfined sheets that:
    - Prograde (step seaward)
    - Retrograde (step landward)
    - Aggrade (build vertically)
- Sheets and unconfined lobes containing
    - Non-amalgamated bodies
- Incised topography fill
    - Amalgamated, multi-storied confined bodies (e.g. incised valleys)
    - Within unconfined lobes

As is explained in the pages that follow, using the above approach geologists infer the processes responsible for that sedimentary rock and so interpret its origin.

Sequence Stratigraphy & Over Simplifications Related to Time

The sedimentary layering of a stratigraphic section has a vast array of dimensional hierarchies. These range from units millimeters thick that might be formed over seconds to thousands of feet thick and formed of millions of years. As much of the literature related to these surfaces indicates, it should be recognized that whatever the dimension of a layer is and whatever the time involved in its deposition, each layer is bounded by surfaces that transgress time (Wheeler, (1958); Middleton, (1973); Vail et al (1977); Galloway, (1989); Catuneanu, et al, (1998); Schwarzacher, (2000); Catuneanu, (2002); Embry, (2002); Cross, and Lessenger, (*submitted*)). This means an interpretation of the depositional setting for a section cut by these diachronous surfaces contravenes Walther's Law. Most interpretators accept and take into consideration that the layered units bounded by these surfaces formed at different times, and recognize that the subdividing surfaces are of a higher order frequency than the time envelope of the parasequence being considered. In other words the situation is simplified when the surfaces are taken to represent instances in time between which sediments continuously accumulated. Thus the surfaces of the layers transgress time and the sediments filling between these surfaces also transgress time while being continuously reworked through a series of geological events.



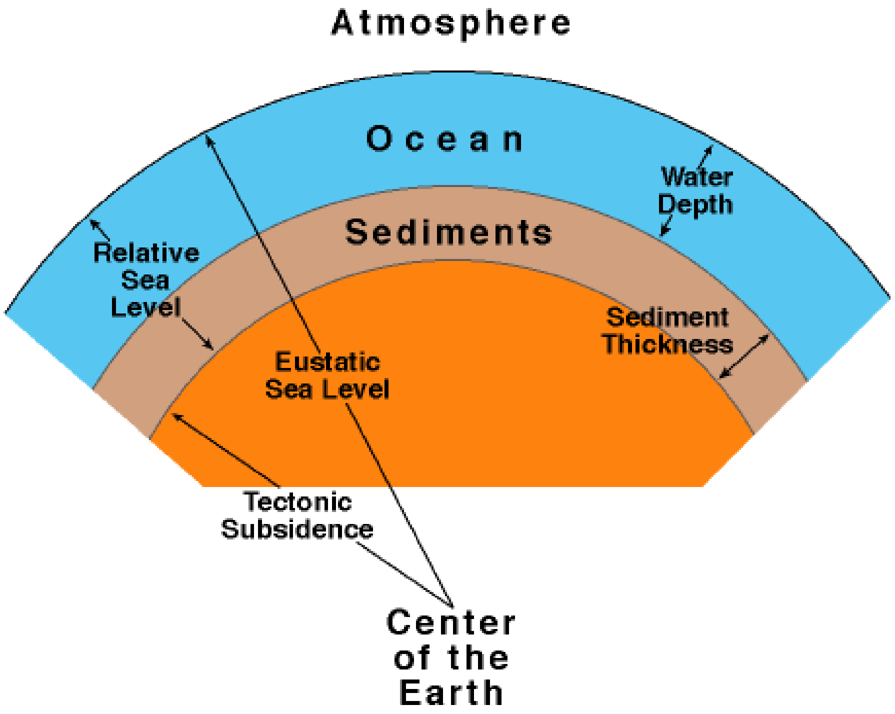
The Figure displays a hierarchy of sedimentary structures: A. Flaser structures from an intertidal flat setting in which the individual components probably accumulated over minutes but the whole section may represent tidal cycles over months (Bar Scale - 2 cm); B. Cross bedded Ordovician carbonates from a beach or nearshore shallow shoal setting that probably represent accumulation and reworking over several years; and C. Flat bedded Mississippian downslope siliciclastic fan deposits in which each bed may have accumulated over a period of hours but whole section encompasses potentially hundreds of thousands of years (Bar Scale - 1 M).

Thus it should be recognized that in sedimentary interpretation the application of Steno's principles and Walther's Law provide powerful and useful simplifications that assume the sediments packaged by surfaces accumulated within discrete moments of time. If one thinks about this, these simplifications don't contravene logic (which is literally Fuzzy) and aid in the interpretation of the sedimentary section. The above discussion provides a general introduction to the subdivision of the sedimentary section by the surfaces listed above and their relationship to base level change. For for a more complete and thorough discussion of this topic you should read Catuneanu (2002).

Accommodation

The Accommodation Space Equation

Over long time scales (10^5 - 10^8 years), sediment accumulation is strongly controlled by changes in eustatic sea level, tectonic subsidence rates, and climatic effects on the production of sediment. Several of these factors are linked to one another through the accommodation space equation. This balance of terms is most easily explained for marine sediments, but can be modified easily to include terrestrial sedimentation. A number of processes can cause the surface of the oceans to move up or down relative to the center of the earth. This distance from the sea surface to the center of the earth is eustatic sea level. In addition, the lithosphere can also move up or down relative to the center of the earth. Changes in the distance from some arbitrarily chosen reference horizon and the center of the earth are called uplift or subsidence. The distance between this reference horizon and the sea surface is called relative sea level or accommodation space.



Acommmodation space can be filled with sediments or water. The distance between the sediment/water interface and the sea surface is known as water depth. The accommodation space not filled with water is filled with sediment. The rates of change of tectonic subsidence, eustatic sea level, sediment thickness and water depth are linked to one another through the accommodation space equation:

$T + E = S + W$

where T is the rate of tectonic subsidence, E is the rate of eustatic sea-level rise, S is the rate of sedimentation, and W is the rate of water depth increase (or deepening). These four variables are defined such that positive values correspond to tectonic subsidence and eustatic sea-level rise (factors that increase accommodation space) and sediment accumulation and water depth increase (factors that reflect filling of accommodation space). Reversing the signs of these variables accommodates tectonic uplift, eustatic sea-level fall, erosion, and shallowing of water depth, respectively.

The accommodation space equation represents a simple volume balance, with the terms on the left controlling the amount of space that can be occupied by sediments or water and the terms on the right describing how much water or sediment fills the accommodation space. As written, the equation is an approximation. In reality, sediment thickness and water depth must be corrected for compaction of sediments and for the isostatic effects of newly deposited sediment.

Through section measurement, changes in sediment thickness can be known, and through facies analysis, changes in water depth can be known or approximated. However, without outside information, the rates of eustatic sea-level change and tectonic subsidence cannot be isolated, nor can their effects be distinguished from one another for a single outcrop. In other words, there is no unique solution to this equation because it has two unknowns. Thus, it is impossible in most cases to ascribe water depth or sedimentation changes to eustasy or tectonics without having regional control or outside information. Backstripping is a method of analysis that iteratively solves the accommodation space to measure changes in relative sea level through time. Although as pointed out earlier that no unique solution exists for this equation, solving it for relative sea level can provide useful insights into eustasy and tectonics. These data may then be used to date the timing of rifting and orogeny, to constrain estimates of lithospheric thickness, or to understand global CO_2 cycles and global patterns of sedimentation.

Causes of Eustatic Sea-Level Change

Changes in eustatic sea level arise from either changes in the volume of ocean basins or changes in the volume of water within those basins. The volume of ocean basins is controlled primarily by the rate of seafloor spreading and secondarily by sedimentation in ocean basins. Because hot and young oceanic lithosphere is relatively buoyant, it floats higher on the asthenosphere and displaces oceanic waters upwards and onto continents. Older and colder oceanic lithosphere is denser, floats lower on the asthenosphere, and allows oceanic waters to stay within ocean basins. Long-term (10^2 k.y. - 10^5 k.y.) changes in the global rate of seafloor spreading can change the global average age and density of oceanic lithosphere, resulting in tens to a couple hundred meters of eustatic change. Filling of ocean basins with sediments derived from continental weathering is a relatively slow and minor way of changing ocean basin volumes and is capable of meters to tens of meters of eustatic change over tens to hundreds of millions of years.

The three most important controls on the volume of seawater are glaciation, ocean temperature, and the volume of groundwater. Continental and mountain glaciation is perhaps the most efficient and rapid means of storing and releasing ocean water. Due to Archimede's principle, ice caps over polar oceans do not affect eustatic sea level, so frozen seawater must be placed on a landmass to lower eustatic sea-level. Continental glaciation is capable of driving high amplitude (10 - 100 m) and high frequency (1 - 100 k.y.) eustatic changes. Because water expands at temperatures higher and lower than 4 degrees C, and because the depths of the oceans average around 5 km, small changes in the temperature of seawater can lead to significant changes in ocean water volume. Changes in water temperature can drive a few meters of eustatic change over short time scales (0.1 - 10 k.y.). Ocean water is continuously being recycled through continents as groundwater and surface water, such as rivers and lakes. Over relatively short time scales (0.1 - 100 k.y.), changes in the amount of water sequestered on the continents can cause up to a few meters of eustatic change.

Causes of Tectonic Subsidence

Tectonic subsidence is also called driving subsidence and is distinguished from the isostatic effects of sediment and water loads. Tectonic subsidence, as its name implies, is driven by tectonic forces that affect how continental lithosphere floats on the asthenosphere. Three main mechanisms that affect this isostatic balance and therefore drive tectonic subsidence include stretching, cooling, and loading.

Stretching of continental lithosphere in most situations results in the replacement of relatively light continental lithosphere with denser asthenosphere. The resulting stretched and thinned lithosphere sinks, causing tectonic subsidence. Stretching occurs in several types of sedimentary basins including rifts, aulacogens, backarc basins, and cratonic basins.

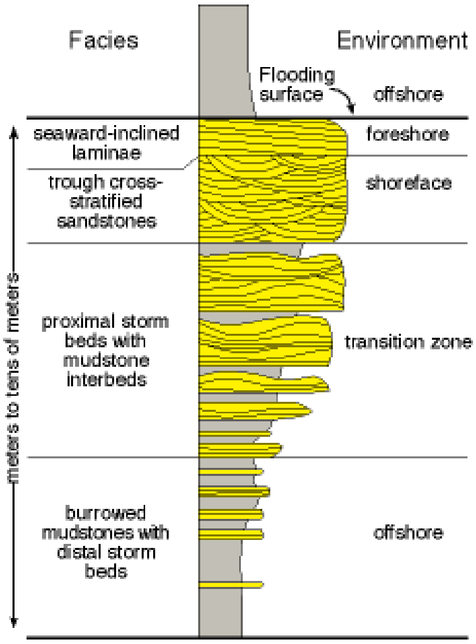
Cooling commonly goes hand-in-hand with stretching. During stretching, continental lithosphere is heated, becomes less dense, and tends to uplift from its decreased density (the net effect in a stretched and heated basin may result either in uplift or in subsidence). As continental lithosphere cools, it becomes denser and subsides. Cooling subsidence decreases exponentially with time yet can cause a significant amount of subsidence hundreds of millions of years following initial cooling. Cooling subsidence is especially important on passive margins and in cratonic basins.

Tectonic loading can also produce subsidence. The additional weight of tectonic loads such as accretionary wedges or fold and thrust belts causes continental lithosphere to sink, leading to tectonic subsidence. Because the lithosphere responds flexurally, the subsidence occurs not only immediately underneath the load, but in broad region surrounding the load. Tectonic loading is particularly important in orogenic regions such as foreland basins.

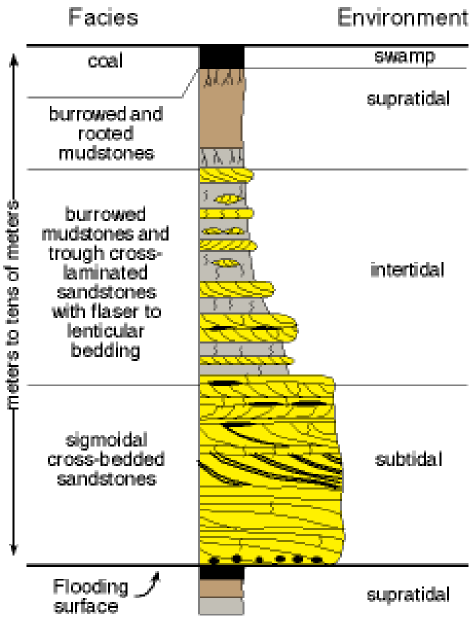
Parasequences

Expression

Parasequences are defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces. In addition to these defining characteristics, most parasequences are asymmetrical shallowing-upward sedimentary cycles.



By genetically related, it is meant that all facies within a parasequence were deposited in lateral continuity to one another, that is, Walther's Law holds true within a parasequence. So, for a typical siliciclastic wave-dominated shoreline, a particular suite of facies should occur in a predictable order. A parasequence that spanned all of these facies would begin with bioturbated offshore mudstones, pass through the storm beds of the transition zone or lower shoreface, continue through the trough crossbedding of the shoreface, pass upwards into the seaward inclined laminae of the foreshore, and be capped by a backshore or coastal plain coal bed. In reality, a single parasequence at a single outcrop rarely passes through all of these facies, but instead includes only a portion of this facies succession; however, all of the facies that do occur appear in the correct order as predicted by Walther's Law. For example, a typical sandy wave-dominated parasequence in an outcrop might include only offshore and transition zone facies, or only shoreface, foreshore, and coastal plain facies, but offshore facies would not be overlain by coastal plain facies within a single parasequence. A parasequence along a deltaic coastline would show a similar coarsening-upward succession, although it would differ in the sedimentary structures developed.



A parasequence developed on a muddy siliciclastic shoreline would have a different suite of facies, but they would also be arrayed vertically in a shallowing upward order and facies relationships would obey Walther's Law. A typical muddy shoreline parasequence would start with cross-bedded subtidal sands, continue with interbedded bioturbated mudstones and rippled sands of the intertidal, and pass upwards into entirely bioturbated and possibly coaly mudstones of the supratidal.

The flooding surfaces that define the top and base of a parasequence display abrupt contacts of relatively deeper-water facies lying directly on top of relatively shallow-water facies. Rocks lying above and below a flooding surface commonly represent non-adjacent facies, such as offshore shales directly overlying foreshore sands or basinal shales directly overlying mid-fan turbidites. Thus, Walther's Law cannot be applied across flooding surfaces. Given that many parasequences are meters to tens of meters thick, this radically reduces the scale at which Walther's Law can be applied. Cases where Walther's Law has been applied to sections hundreds to thousands of meters thick are nearly always incorrect.

Flooding surfaces may also exhibit small scale erosion, usually of a meter or less. Flooding surfaces may be mantled by a transgressive lag composed of shells, shale intraclasts, calcareous nodules, or siliciclastic gravel; such lags are usually thin, less than a meter thick. Flooding surfaces may display evidence of firmgrounds, such as *Glossifungites* ichnofacies, or hardgrounds that may be bored, encrusted, and possibly mineralized.

Origin and Scale

A parasequence represents a single episode of progradation, that is, the seaward movement of a shoreline. This seaward shoreline movement produces the familiar shallowing-upward succession seen within parasequences. The shallowing-upward succession indicates that accommodation space is being filled more rapidly than it is being created, and some evidence suggests that in some cases, accommodation space is created only at flooding surfaces and not during the bulk of a parasequence.

Flooding surfaces represent a relative rise in sea level, such that accommodation space is being created at a faster rate than it is being filled with sediment. Although these rapid rises in accommodation space are commonly attributed to eustatic sea-level rise, some flooding surfaces are clearly attributable to earthquake-induced subsidence or to delta switching or similar autocyclic mechanisms.

Scale is not part of the definition of a parasequence. However, parasequences are commonly meters to tens of meters thick and they commonly represent durations of tens to hundreds of thousands of years. Many authors confuse these typical scales with the definition of a parasequence, and erroneously assume that any small cycle must be a parasequence and that any long or thick cycle cannot be a parasequence. This is not the case as some meter-thick cycles clearly do not have a parasequence structure and some hundred to thousand meter-thick cycles do display a parasequence structure.

Lateral and Vertical Relationships within a Parasequence

One of the most powerful aspects to recognizing parasequences is understanding and applying the predictable vertical and lateral facies relationships within parasequences. As stated earlier, facies reflect increasingly shallower environments upwards within a parasequence. Although a complete vertical succession of facies can be compiled from a suite of parasequences, most parasequences will display only a portion of the entire shallowing-upward succession of facies.

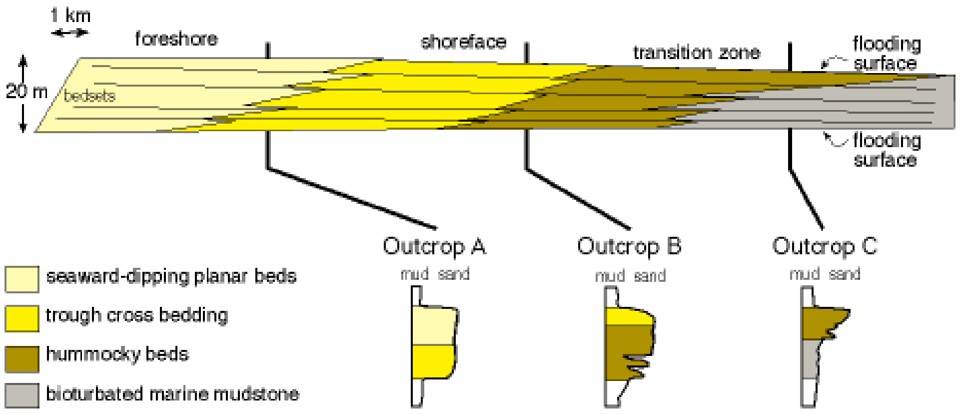


figure adapted from Van Wagoner et al. (1990)

Because shallow water facies within a parasequence will pinch out laterally in a downdip direction and deeper water facies within a parasequence will pinch out in an updip direction, the facies composition of a single parasequence changes predictably updip and downdip. Thus, a single parasequence will not be composed of the same facies everywhere, but will be composed of deeper water facies downdip and shallower water facies updip, as would be expected. Because parasequence boundaries represent a primary depositional surface, that is, topography at the time of deposition, flooding surfaces will tend to be relatively flat but dip slightly seaward at angles typical of continental shelves. Finally, parasequence boundaries may become obscure in coastal plain settings and in deep marine settings because of a lack of facies contrast necessary to make flooding surfaces visible.

Parasequence Sets and Stacking Patterns

In most cases, there will not be simply one parasequence by itself, but there will be a series of parasequences. Sets of successive parasequences may display consistent trends in thickness and facies composition and these sets may be progradational, aggradational, or retrogradational.

Progradational Stacking

In a progradational set of parasequences, each parasequence builds out or advances somewhat farther seaward than the parasequence before. Because of this, each parasequence contains a somewhat shallower set of facies than the parasequence before. This produces an overall shallowing-upward trend within the entire parasequence set and the set is referred to as a progradational parasequence set or is said to display progradational stacking. In a single outcrop, a progradational parasequence set can be recognized by the progressive appearance of shallower-water facies upward in the parasequence set as well as the progressive loss of deeper-water facies upward in the parasequence set. For example, in a set of progradationally stacked parasequences, perhaps all of the parasequences contain shoreface and foreshore facies, but only the uppermost parasequences may contain the coastal plain coal, and only the lowermost parasequences may contain offshore and transition zone facies.

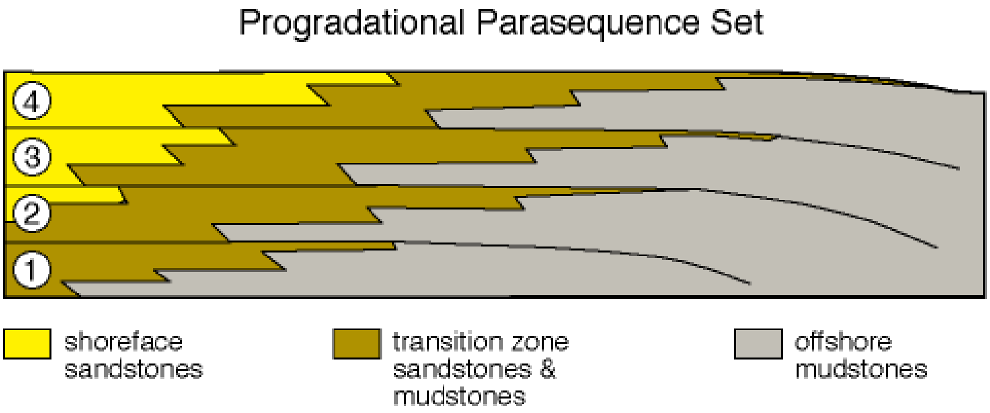


figure adapted from Van Wagoner et al. (1990)

In a cross-section, a progradational parasequence set can be recognized by the seaward movement of a particular facies contact at an equivalent position in a parasequence. For example, the contact between the shoreline sands and the coastal plain facies at the top of each parasequence will appear to move farther basinward in each successive parasequence. Likewise, the same contact at the base of each parasequence will appear to move farther basinward in each successive parasequence.

Progradational stacking results when the long-term rate of accommodation is exceeded by the long-term rate of sedimentation. In this way, accommodation space is filled more rapidly than it is created, water depth becomes shallower, and facies increasingly move farther seaward over time. Each parasequence is shallowing-upward and is bounded by a flooding surface, across which water depth abruptly increases. However, the shallowing gained in one parasequence overshadows any deepening across the underlying flooding surface, resulting in a net seaward movement of facies relative to the previous parasequence.

Aggradational Stacking

In an aggradational set of parsequences, each parasequence progrades to roughly the same position as the previous parasequence. Thus, each parasequence contains essentially the same suite of facies as the parasequences above and below. This lack of overall facies change results in no net vertical trend in water depth. Such a set is called an aggradational parasequence set or is said to display aggradational stacking. In a single outcrop, an aggradational parasequence set can be recognized by the similarity of facies composition in each successive parasequence. No new deeper or shallower water facies will tend to appear near the top or base of the parasequence set.

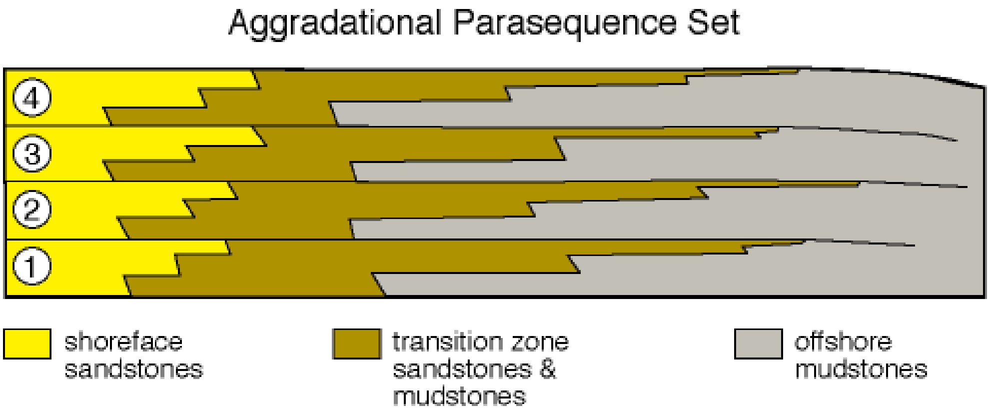


figure adapted from Van Wagoner et al. (1990)

In a cross-section, an aggradational parasequence set can be recognized by the relative stability of any particular facies contact at an equivalent position in a parasequence. For example, the contact between the shoreline sands and the coastal plain facies at the top of each parasequence will appear to stay at essentially the same position in each successive parasequence. Facies contacts rarely remain at exactly the same position, so aggradational parasequence sets are commonly characterized by relatively minor facies shifts that display no clear long-term trend.

Aggradational stacking results when the long-term rate of accommodation closely matches the long-term rate of sedimentation. In this way, accommodation space is filled about as rapidly as it is created, water depth remains constant from one parasequence to the next, and facies show no net landward or seaward movement. Although each parasequence is shallowing-upward and is bounded by a flooding surface, the shallowing in each parasequence closely balances the deepening at the underlying flooding surface, resulting in no net shift of facies from one parasequence to the next.

Retrogradational Stacking

In a retrogradational set of parasequences, each parasequence progrades less than the preceding parasequence. The result is that each parasequence contains a deeper set of facies than the parasequence below. This net facies shift produces an overall deepening upward trend within the entire parasequence set and the set is referred to as retrogradational parasequence set or is said to display retrogradational stacking. Retrogradational stacking is also commonly called backstepping. In a single outcrop, a retrogradational parasequence set can be recognized by the progressive appearance of deeper water facies upwards within the parasequence set as well as the progressive loss of shallower water facies upwards in the parasequence set. For example, in a set of retrogradationally stacked parasequences, offshore facies might be present in only the uppermost parsequences, and coastal plain coals might be present in only the lowermost parasequences.

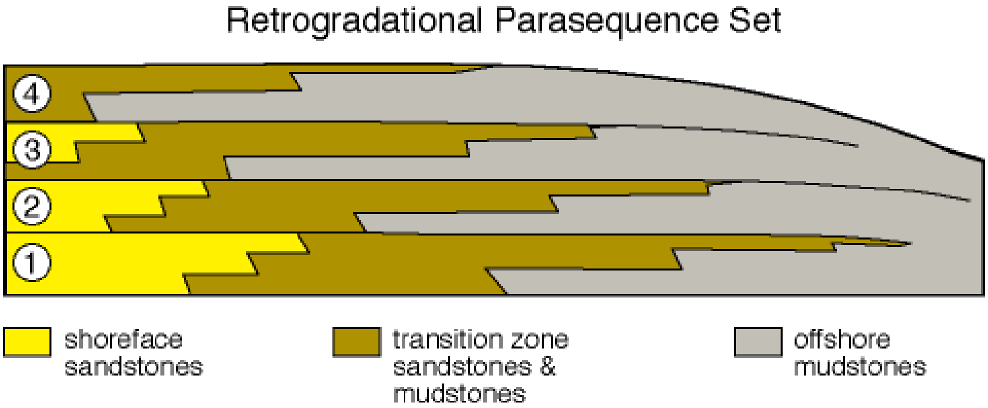


figure adapted from Van Wagoner et al. (1990)

In a cross-section, a retrogradational parasequence set can be recognized by the landward movement of a particular facies contact at an equivalent position in a parasequence. For example, the contact between the shoreline sands and the coastal plain facies at the top of each parasequence will appear to move farther landward in each successive parasequence.

Retrogradational stacking results when the long-term rate of accommodation exceeds the long-term rate of sedimentation. In this way, accommodation space is created more rapidly than it is filled, water depth becomes deeper, and facies increasingly move farther landward. Although each parasequence is shallowing-upward, the amount of deepening at the flooding surface exceeds the amount of shallowing in the following parasequence, producing a net overall deepening within the parasequence set.

Depositional Sequences

A depositional sequence is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities. Like the definition of a parasequence, this definition obscures many of the significant features of a depositional sequence. What the definition does emphasize is that every sequence is bounded above and below by unconformities, or by correlative conformities, surfaces that correlate updip to an unconformity. An unconformity is somewhat narrowly defined here as a surface formed through subaerial exposure and erosion. Furthermore, every depositional sequence is the record of one cycle of relative sea level. Because of this, depositional sequences have a predictable internal structure consisting of major stratal surfaces and systems tracts, which are suites of coexisting depositional systems, such as coastal plains, continental shelves, and submarine fans. In vertical succession, all depositional sequences are composed of the following elements in this order: sequence boundary, lowstand systems tract, transgressive surface, transgressive systems tract, maximum flooding surface, highstand systems tract, and the following sequence boundary.

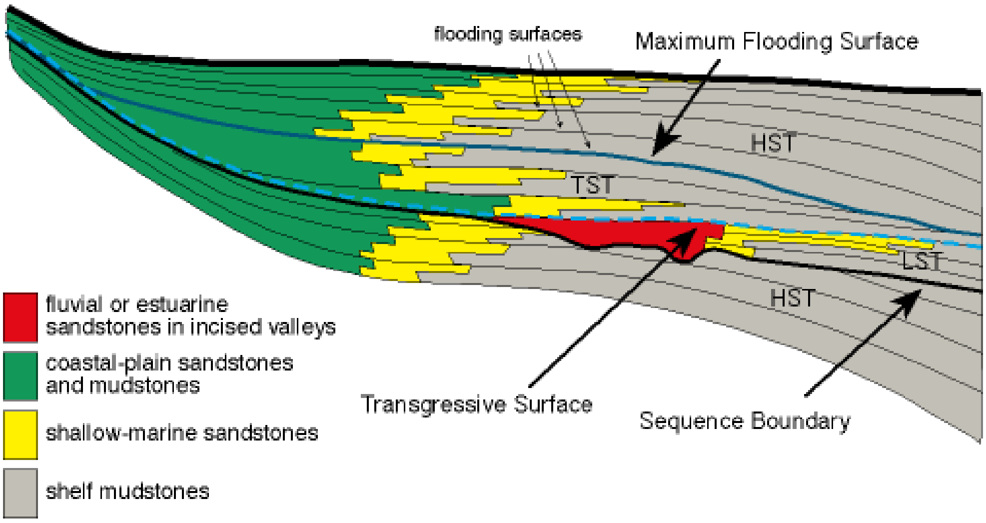


figure adapted from Van Wagoner et al. (1990)

Lowstand Systems Tract

The lowstand systems tract is the set of depositional systems active during the time of relatively low sea level following the formation of the sequence boundary. If a distinct shelf-slope break exists and relative sea level has fallen sufficiently, the lowstand systems tract may include two distinct parts, the lowstand fan and the lowstand wedge.

The lowstand fan consists of a basin-floor submarine fan. This fan may contain a series of feeder channels as well as distinct fan lobes. The lowstand fan typically displays aggradational stacking and is overlain by the lowstand wedge. During the time of lowest relative sea levels on siliciclastic margins, rivers begin to incise into the exposed shelf and this sediment is shunted directly off the shelf edge to feed submarine fans.

The lowstand wedge consists of a progradational set of parasequences building out from the pre-existing continental slope. In siliciclastic systems, the lowstand wedge may be characterized by shelf-edge deltas and shorelines. In systems lacking a distinct shelf-slope break or in cases where relative sea level does not fall sufficiently, only a lowstand wedge may form, with no lowstand fan. During the late lowstand, relative sea level begins to rise slowly, allowing the incised valleys to flood and form estuaries. River sediment is trapped in these estuaries and is prevented from reaching the shelf; this trapping becomes even more effective during the transgressive systems tract.

Following the relative fall in sea level that produces the sequence boundary, relative sea-level begins to bottom out and and eventually begins to rise slowly, but at a very slow rate. This slow rate of accommodation coupled with relatively high supply of sediment results in the progradational stacking typical of the lowstand wedge.

Transgressive Systems Tract

The transgressive systems tract consists of a retrogradational set of parasequences. It is underlain by the transgressive surface and overlain by the maximum flooding surface. As in any retrogradational set of parasequences, flooding surfaces within the transgressive systems tract are unusually prominent and display strong facies contrasts and pronounced deepening. These flooding surfaces may display variable but commonly strong degrees of sediment starvation, discussed in more detail below. Because the parasequences backstep, the transgressive systems tract displays an overall deepening-upward succession, although each component parasequence is shallowing-upward. In siliciclastic systems, much sediment is trapped in estuaries, so the continental shelf is relatively starved of sediment during major transgressions. A relatively minor amount of sand is reworked along the shoreline and little sediment is transported to the outer continental shelf. Consequently, individual parasequences of the TST are relatively thin nearshore sands with thinner offshore deposits and the TST as a whole is therefore commonly quite thin relative to other systems tracts.

As relative sealevel continues to rise, accommodation space is produced at a faster rate than it can fill with sediments, and a retrogradational set of parasequences forms. At each flooding surface in the transgressive systems tract, the short term relative rise in sea level adds to the long term rise in relative sea level to produce an unusually rapid rise and a highly pronounced flooding surface.

Highstand Systems Tract

The highstand systems tract consists of an aggradational to progradational set of parasequences that overlies the maximum flooding surface and that is overlain by the next sequence boundary. As the parasequences pass from aggradational to progradational stacking, the flooding surfaces are increasingly subdued at the expense of overall shallowing

In siliciclastic systems, estuaries have either been filled with sediment by the beginning of the highstand systems tract or are finally filled in the earliest phases of the highstand systems tract. Once sediment is no longer trapped in estuaries, rivers are free to build seaward and form deltas. In portions of coastlines between deltas, sandy wave-dominated shoreline deposits may form.

During the highstand systems tract, the rate of relative sea level rise begins to slow and relative sea level eventually begins to fall prior to the next sequence boundary. Throughout the highstand systems tract however, accommodation space is created or destroyed at a relatively slow rate. Coupled with the increased supply of sediment to the shelf as estuaries are filled, progradational stacking is increasingly favored over aggradational stacking. As relative sealevel begins to fall, a new sequence boundary begins to form; this sequence boundary will begin to erode into the underlying highstand systems tract. Although the highstand systems tract is most prone to erosional removal during sequence boundary formation, even lower systems tracts or entire sequences may be removed during extremely low or long relative sea-level lowstands.

Surfaces

Sequence Boundary

The sequence boundary is an unconformity updip and a correlative conformity downdip. Where it is an unconformity, it is a surface of subaerial exposure and erosion; however, the expression of those features in an individual outcrop may or may not be obvious. In places, an unconformity may be marked by obvious erosion, such as a major incised channel or a bevelling of structurally tilted underlying strata. Regionally, unconformities may display up to tens or sometimes hundreds of meters of relief. In siliciclastic systems, this relief is generated principally by downcutting rivers. In the undissected regions between rivers, called interfluves, paleosols may mark an unconformity, and their presence may be indicated by caliche nodules or rooted horizons.

Downdip at its correlative conformity, a sequence boundary is commonly marked by an abrupt basinward shift in facies. This abrupt shift is called a forced regression by some workers to distinguish it from a normal regression in which a shoreline moves seaward simply due to sedimentation. An abrupt basinward shift of facies is manifested in an outcrop by an abrupt shallowing, such as shoreface sediments directly overlying offshore sediments or mid-fan turbidites directly overlying basinal shales. As facies above and below such a basinward shift in facies commonly represent non-adjacent environments, this surface is abrupt and Walther's Law cannot be applied across it. Minor submarine erosion may be associated with this abrupt basinward shift of facies. Farther downdip, the correlative conformity may display no obvious facies contrast or other unusual features; the position of the sequence boundary in these cases can only be approximated.

Sequence boundaries are generated by a relative fall in sea level. As this is a relative fall in sea level, it may be produced by changes in the rate of tectonic subsidence or by changes in the rate of eustatic rise, as long as those changes result in a net loss of accommodation space. Early models of sequence boundary formation argued that the sequence boundary formed at the time of maximum rate of fall, but subsequent models suggest that the age of the sequence boundary can range in age from the time of maximum rate of fall to the time of eustatic lowstand.

Transgressive Surface

The lowstand systems tract is commonly capped by a prominent flooding surface called the transgressive surface. The transgressive surface represents the first major flooding surface to follow the sequence boundary and is usually distinct from the relatively minor flooding surfaces that separate parasequences in the lowstand systems tract.

The transgressive surface may be accompanied by significant stratigraphic condensation, particularly in nearshore settings, which may be starved of sediment because of sediment storage in newly formed estuaries. Typical features indicating condensation are discussed in more detail below.

Following the relatively low rates of accommodation during the lowstand systems tracts, relative sea level begins to rise at an increasing rate. When this long-term rise is coupled with the short-term rise that forms a parasequence boundary, a major flooding surface is formed. The first of the series of these flooding surfaces is called the transgressive surface. In updip areas characterized by subaerial exposure and erosion during the lowstand systems tract, the transgressive surface and sequence boundary are merged into a single surface. Such situations are common in slowly subsiding regions such as in cratonic regions and the landward areas of passive margins.

Maximum Flooding Surface

The maximum flooding surface caps the transgressive systems tract and marks the turnaround from retrogradational stacking in the transgressive systems tract to aggradational or progradational stacking in the early highstand systems tract. The maximum flooding surface represents the last of the significant flooding surfaces found in the transgressive systems tract and is commonly characterized by extensive condensation and the widest landward extent of the marine condensed facies.

Condensation, that is, the preservation of relatively long geologic timespans in a relatively thin layer of sediment, can be indicated by many sedimentary features. Condensation or slow net deposition allows more time for diagenetic reactions to proceed, so condensed sections are commonly enriched in normally rare authigenic minerals such as glauconite, phosphate, pyrite, and siderite. Carbonate cementation is allowed more time to proceed and hardgrounds may form, and these may be subsequently mineralized with iron, manganese, and phosphorite crusts, as well as become bored or encrusted by organisms. The slow accumulation of sediment allows more skeletal material to accumulate and condensed sections may be indicated by unusually fossiliferous horizons or shell beds. Likewise, slow rates of sediment accumulation allow burrowing organisms more time to rework a given package of sediment, so burrowed surfaces are common in condensed sections. Slow rates of accumulation allow normally rare materials like micrometeorites and volcanic ashes to accumulate in greater abundances. Shales at condensed sections are commonly radiogenic as a result of increased scavenging of radioactive elements from the water column; such 'hot shales' display a strong positive response on gamma ray logs.

Sediment starvation is not the only process leading to slow accumulation rates, and many condensed sections are characterized by sediment bypassing, in which sediment is either moving through the system as suspended load or as bedload. When sediment moves through as bedload but fails to accumulate significantly, the condensed section is commonly characterized by numerous internal erosion surfaces and can have a quite complicated internal stratigraphy.

In outcrop, the maximum flooding surface is recognizable by the deepest water deposits within a sequence. In cross section, the maximum flooding surface is marked by the farthest landward extent of deep-water facies. In distal areas where the transgressive systems tract is absent, the maximum flooding surface may merge with the transgressive surface.

Early models of sequence stratigraphy argued that the maximum flooding surface coincides roughly with the most rapid relative rate of sea level rise, after which sea level rise begins to slow. Subsequent models have demonstrated that the maximum flooding surface corresponds more closely in time with the highest stand of eustatic sea level, rather than the time of maximum rate of rise.

Type 1 and Type 2 Sequences

Not all relative falls in sea level occur at a fast enough rate to expose the continental shelf. For example, during a eustatic fall, a rapidly subsiding margin may still experience a relative rise in sealevel, provided the rate of eustatic fall is less than the rate of subsidence. Early seismic studies recognized two types of sequences reflecting the case of sea-level fall below the shelf-slope break (type 1) and the case where sea level does not fall below this break (type 2). Although there has been much subsequent confusion about the application of these two types to outcrop studies, their definitions have been modified such that a type 1 sequence now refers to one in which there is a relative fall in sea level below the position of the present shoreline and a type 2 sequence refers to a sequence in which the relative fall in sea level does not force a shift in the position of the shoreline. Type 1 sequences were discussed above in the preceeding sections; type 2 sequences are discussed below.

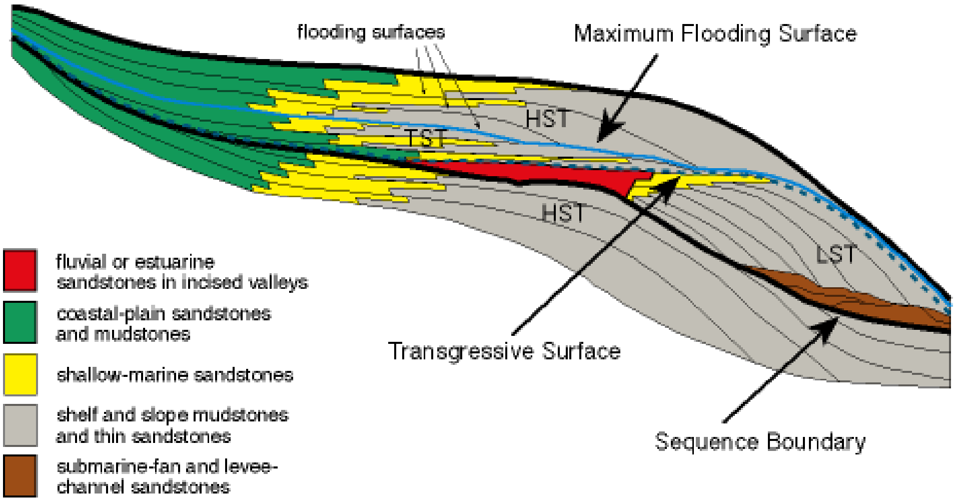


figure adapted from Van Wagoner et al. (1990)

Type 2 sequences (shown below) are similar to type 1 sequences (shown above) in nearly all regards except for the extent of the sequence-bounding unconformity and its expression in the marine realm. In addition, the two sequences differ in the name of the systems tract lying above the sequence boundary but below the transgressive surface .

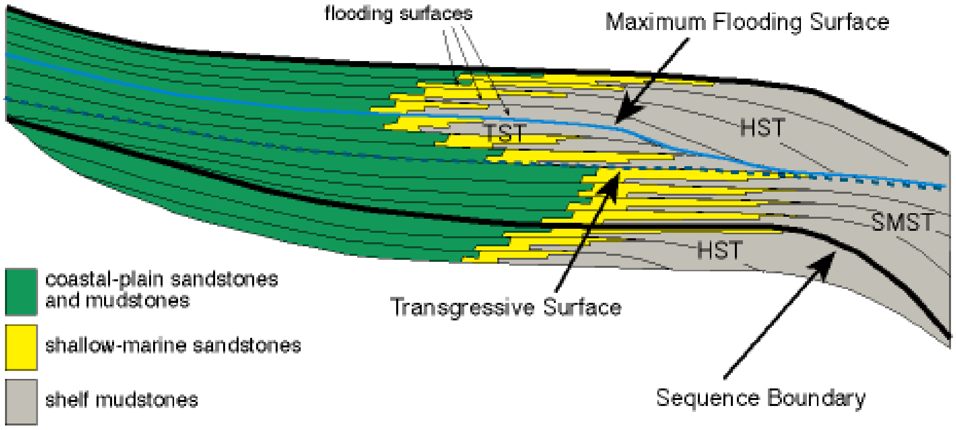


figure adapted from Van Wagoner et al. (1990)

In a type 2 sequence, the extent of the sequence-bounding unconformity can reach seaward only to the position of the previous shoreline, but no further. In other words, none of the marine areas of the previous highstand are subaerially exposed during a type 2 sequence boundary. Updip of these areas, the sequence bounding unconformity is expressed as for a type 1 sequence, but no incised valley forms as sealevel does not fall far enough for incision. In the marine realm, no basinward shift of facies occurs as in a type 1 sequence, and the type 2 sequence boundary is characterized only by a slight change in stacking patterns from increasingly progradational in the underlying highstand to decreasingly progradational (possibly aggradational) above the sequence boundary.

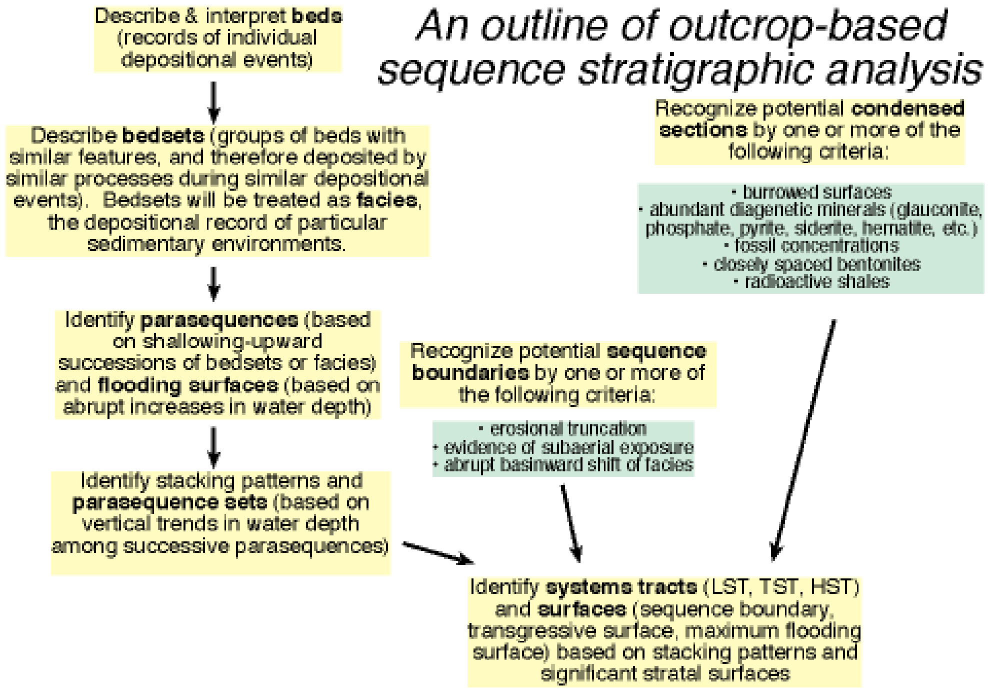
Detecting this subtle transition in marine sections may be difficult to impossible and many type 2 sequence boundaries probably go undetected.

The shelf margin systems tract in a type 2 sequence is equivalent in stratigraphic position to the lowstand systems tract of a type 1 sequence. As stated above, the shelf margin systems tract is characterized by aggradational stacking. Like the lowstand systems tract, the shelf margin systems tract is capped by the transgressive surface.

In general, far more type 1 sequences have been reported than type 2 sequences, possibly in part reflecting their comparative difficulty or ease of detection. Some workers have gone so far as to question the existence of any type 2 sequences.

Application to Outcrops

Although sequence stratigraphy was originally designed for seismic sections, sequence principles can be readily applied to outcrop, core, and well logs . The first step in this approach is to interpret individual beds in terms of depositional events, including an evaluation of the shear stress in the environment, the type of flow (currents, waves, tides, combined flow), bioturbation and trace fossils, etc. This information is critical for the next step, to recognize bedsets, that is groups of beds that record similar depositional processes, and to interpret those bedsets as facies, the records of particular depositional environments. These steps are critical because errors at this point may cause errors in interpretations of relative depth, which in turn affects the recognition of parasequences and stacking patterns. Solid facies work is essential for a solid sequence analysis.



An outline of outcrop-based sequence stratigraphic analysis

From successions of facies in an outcrop, shallowing-upward successions can be recognized as well as flooding surfaces such that parasequences can be delimited. Vertical trends in the range of water depths present in successive parasequences can be used to identify stacking patterns and to recognize surfaces that mark the turnarounds from one parasequence set to the next. Potential sequence boundaries should be identified at this step based on one or more of the following criteria: clearly defined erosional truncation, direct evidence of subaerial exposure, or abrupt basinward shifts of facies. Likewise, potential condensed sections should be recognized on the basis of unusual burrowed surfaces, abundant diagenetic materials, fossil concentrations, closely spaced bentonite beds, or radioactive shales. Condensed sections may, but do not necessarily, lie along the maximum flooding surface.

From the recognition of parasequence sets and potential sequence boundaries and condensed sections, systems tracts and major stratal surfaces (sequence boundary, transgressive surface, and maximum flooding surface) can be recognized. It is important to stress that not all of these surfaces or systems tracts may be present within any given sequence in an outcrop. The absence of one or more surfaces or systems tracts may provide important clues as to the relative position of the outcrop within the basin. For example, lowstand systems tracts are commonly absent in updip areas where the transgressive surface and sequence boundary are merged as one surface. In such areas, significant portions of the highstand systems tract may have eroded away and the sequence boundary is marked by the beginning of retrogradational stacking. In downdip areas, the transgressive and highstand systems tracts may be thin and relatively mud-rich, whereas the lowstand systems tract may be characterized by the abrupt appearance of thick sandy facies. Many more variations are possible and many basins are characterized by a typical pattern of sequence architecture.

Chronostratigraphic Applications

Many of sequence stratigraphic surfaces can serve as useful time-markers. Parasequence boundaries are commonly useful correlation horizons in local studies. Because individual parasequences may look so similar, long-distance correlation of parasequence boundaries is prone to error and must be checked with other means of correlation.

For depositional sequences, the transgressive surface and maximum flooding surface can also be useful correlation markers, at least within a basin. Because the transgressive and maximum flooding surfaces are defined by changes in stacking patterns (from progradational to retrogradational and from retrogradational to progradational, respectively), they are sensitive to regional changes in sediment supply and long-term accommodation driven by differences in subsidence rate. Consequently, correlation of these two surfaces over long distances becomes increasingly less reliable.

The sequence boundary has attracted the most attention as a potentially correlatable and chronostratigraphically significant surface. By chronostratigraphically significant, it is meant that all rocks overlying the sequence boundary are younger than all rocks below the sequence boundary, throughout its extent. Although this is true along a cross-section parallel to depositional dip, it is less certain along strike or in different sedimentary basins. Clearly, tectonically produced sequence boundaries will be of different ages in different basins. Early studies suggested that eustatically generated sequence boundaries coincide with time of maximum rate of fall in eustatic sea level and are therefore chronostratigraphically significant. However, more recent studies suggest that the timing of the sequence boundary can vary from the time of maximum rate of fall to the time of the lowest position of eustatic sea level. In particular, faster tectonic subsidence rates and higher rates of sediment supply may cause the timing of the sequence boundary to be delayed. If these modeling results are correct, then the sequence boundary could differ in age by as much as 1/4 of the duration of a eustatic cycle.

Carbonate Sequence Stratigraphy

Although much of the previous discussions have drawn on siliciclastic margins as examples, sequence analysis can be readily applied to carbonate systems as well. Carbonates have several unusual features relative to siliciclastics that make their response to relative sea-level changes and their expression of sequence stratigraphic elements somewhat different.

First, when subaerially exposed, carbonates are much more prone to dissolution than erosion like siliciclastics. Consequently, sequence boundaries in carbonates are more commonly expressed as karst surfaces with solution relief, collapsed breccias, paleosols, and silicification. Many additional exposure features are visible petrographically (pendant and meniscus cements, vadose silt, grain dissolution, neomorphism, etc.) or isotopically (negative shifts in delta C-13).

Second, carbonate sediment production is largely in situ rather than transported from outside the basin as in siliciclastics. Whereas relative sea-level rise can trap siliciclastic sediments in estuaries and coastal lagoons, moderate rates of relative sea-level rise allow the carbonate factory to produce at much higher rates. Consequently, transgressive systems tracts in carbonate settings can be extremely thick. Likewise, highstand systems tracts in carbonate settings can be much thinner, because, unlike siliciclastic settings, much of the accommodation space generated during the transgressive systems tract is continually filled. Consequently, highstand sediments only fill space generated during the highstand systems tract and not unfilled space generated during the previous transgressive systems tract. Extremely rapid rates of relative sea-level rise can cause a total shutdown in carbonate production, leading to the formation of spectacular condensed sections with extensive hardground formation as well as pyrite and phosphate mineralization.

Because carbonate production can often keep pace with moderate rates of relative sea-level rise, some carbonate settings are characterized by extremely thick sections of peritidal cycles, carbonate parasequences that shallow upwards to supratidal depths. Identifying depth trends over hundreds of peritidal cycles can be difficult or impossible, so stacking patterns can alternatively be recognized by vertical trends in the thickness of peritidal cycles. Upward thickening of successive parasequences without a net water depth change would indicate progressively greater rates of relative sea-level rise while sediment production was always able to keep up with the rise. Such upward thickening of cycles would be interpreted as retrogradational stacking. Upward thinning of peritidal cycles would indicate slowing rates of relative sea-level rise and would be interpreted as progradational stacking.

Except for these differences, application of sequence stratigraphic principles in terms of intepreting beds and bedsets, recognizing parasequences, stacking patterns and parasequence sets, and identifying significant stratal surfaces and systems tracts is nearly identical in approach for carbonates and siliciclastics.

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