Why Do Siliciclastic Shelves Exist? How Do They Differ from "Ramp Margins"? New Sequence Stratigraphic Aspects Vital for Petroleum Exploration*

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Abstract

Elaborating on Seilacher (1982) and Swift & Thorne (1991), the floor of a sea or lake at stillstand aggrades to an equilibrium shelf profile governed by storm erosion (wave + tide + wind drift + hyperpycnal flow), except near deltas where progradation exceeds erosion. Each storm shaves the surface back down to this ideal profile, leaving a subsidence-accommodated increment, transporting the surplus seaward to prograde the adjacent slope. (In contrast, under falling sea level, storms progressively lower the shelf.) The shelf thus widens until the next sea-level rise, unless structurally confined (subduction, transform). Seaward fining (sand to fluid mud) reflects decreasing bottom wave power with increasing water depth, governing the maximum grain size remobilizable at any point along the profile. Thus, each grain size has its own storm wavebase, toward which it moves incrementally; its absolute value (m), controlling shelf gradient, depends on tidal regime and largest storm-wave height (basin specific). Sea-level changes make shelves cyclically drown, build and emerge, forming stacked sequences, e.g. the present continental shelf is the last interglacial highstand shelf, modified by falling-stage and lowstand erosion (submarine, subaerial), then planed by ravinement and drowned by postglacial rise. A ramp margin sensu Exxon has no shelf break. But, in a wider context, a ramp is one flank of a foreland gulf or strait ("closed shelf"), both of which do have a shelf break, at one or both ends, adjoining a flysch trough or ocean (e.g. modern Gulf of Carpentaria-Arafura Sea; Cretaceous Western Interior Seaway). Hence, both of Exxon's Type 1 sequences (ramp, shelf) must occur on ramps and "open shelves"; ramps contain just the proximal part of shelf Type 1 sequences, i.e. shelf-edge LST is remote. Given also the disuse of Type 2 sequences, a new terminology is proposed: Suprashelf vs. Shelf-Edge sequences. Drowning, whether of a ramp or an open shelf, initiates a new, stillstand shelf-slope, perched on the old one, producing a parasequence with clinoforms (e.g. modern innermost shelf). Clinoform height (neglecting compaction) reflects the sum of: (1) pre-drowning water depth; (2) eustatic rise height; and (3) rise duration, which determines deepening by subsidence while the shelf starves (sediment trapped inshore). For example, the long lasting rise from 75 to 73 Ma (Haq), though only c. 50 m, produced clinoforms c. 400 m high in the Western Interior (Lewis Shale).

Introduction

Geologists seldom ask why siliciclastic shelves exist, and how they differ from "ramp margins" (*sensu* Van Wagoner et al., 1988), despite the importance of shelves and ramps in petroleum exploration models (sequence stratigraphy) and in hosting petroleum reservoirs. Modern shelves occur in diverse water bodies, including large lakes (e.g., Great Lakes; Pickrill, 1983), ocean-connected lakes (e.g., Quaternary Black Sea, brackish at highstand), fully marine seas on continental crust (e.g., Timor Sea), and seas or oceans on oceanic crust (e.g., Mediterranean, Atlantic). The term "continental shelf" is used only for oceanic shelves; their origin is unclear, partly due to the effects of Neogene and Quaternary glacioeustasy (Moore and Curray, 1964). Ancient marine shelf deposits are well known (e.g., review by Suter, 2006); ancient lacustrine examples also exist (Higgs, 1991, 2004). This contribution summarizes the literature and offers further ideas, some highly conjectural, on shelves, ramps and their sequence stratigraphy, aimed at provoking discussion and aiding petroleum exploration.

Origin of Shelves

In the old "profile of equilibrium" concept of Fenneman (1902), a marine shelf comprises an inner wave-cut rock platform and a depositional, wave-regulated outer shelf (Fenneman, 1902; Johnson, 1919). This concept was based on observations of shelves bordered by rock cliffs, i.e., coastlines that are currently undergoing uplift, e.g., by glacio-isostatic rebound. In subsiding basins, the situation is different. The newer concept of a constructional (i.e., net long-term deposition), wave-graded shelf, fining seaward from sand at the shoreline to mud at the shelf edge, is now well established (Seilacher, 1982; Pickrill, 1983; Swift and Thorne, 1991; Dunbar and Barrett, 2005).

According to Seilacher (1982, p. 171), a shelf is "an equilibrium profile near the extreme storm wave base", whereby "extreme events would tend to winnow down excessive sediment accumulations to this equilibrium profile, while the winnowed fines would gradually prograde the shelf edge basinwards". In other words, sediment finding itself above the equilibrium profile, due to sediment aggradation since the last erosive storm event (i.e., deposits of that storm and of the ensuing fair-weather period), is shaved back down during the next storm, by a combination of waves and other currents (e.g. tide, wind drift, downwelling, hyperpycnal), leaving behind a subsidence-accommodated increment over the long term (Figure 1). The eroded, surplus sediment is swept over the shelf edge by storm-associated currents, and deposited largely from suspension on the upper slope. This leads to slope oversteepening and repeated sliding and slumping, restoring the equilibrium slope gradient. Thus, whereas the shelf aggrades, and its gradient is controlled by storm erosion, the slope progrades and its gradient is governed mainly by sediment cohesion and gravity. Covey (1986) also envisaged tide and storm currents as being responsible for maintaining long-term, equilibrium, shallow-marine conditions. Numerical models post-dating Seilacher's (1982) paper acknowledge the importance of storm waves in forming shelves (review in Pratson et al., 2004). The addition of tidal currents (cf. ternary 'waves-tides-storms' shelf classification of Johnson and Baldwin, 1996) might produce a deeper equilibrium profile, unless the tide-enhanced erosive power during storms is offset by faster fair-weather sedimentation (e.g., migrating sand dunefields).

In the modern literature, the term "wave base" (fair weather or storm) is usually used to mean the maximum water depth at which waves can move *sand* (e.g., Suter, 2006). However, wave base (Gulliver 1899) was defined by Rich (1951) as "the greatest depth to which the bottom is stirred during storms". Nowadays this depth is termed storm wave base (SWB); its numerical value depends on wave size, governed by fetch. Seaward fining across an ideal shelf, from sand to incohesive (fluid) mud (Figure 2), reflects the decreasing bottom wave power with increasing water depth, governing the maximum grain size remobilizable at any point along the profile. Thus, each grain size has its own storm wave base, or "effective wave-base" (Moore and Curray, 1964), toward which it moves incrementally in successive storms ("progressive sorting"; Swift and Thorne, 1991); its absolute value (m), inferred here to control the shelf gradient, depends mainly on tidal regime and largest storm-wave height. The extent of fluid-mud transport on shelves during storms is only lately becoming appreciated (Bhattacharya and MacEachern, 2009; Macquaker and Bentley, 2009). Storm wave base for fluid mud (SWBfm) may coincide with (and control) the equilibrium shelf-edge depth (Figure 2).

The ideal, seaward-fining shelf of Figure 2 is an oversimplification. In reality, interpreted ancient shelf deposits consist largely of interbedded sandy tempestites and mud (interbedding shown schematically in Figure 2 by zigzag facies boundaries, of unrealistically limited lateral extent). Interbedding reflects variable storm intensity: mud deposited by weaker storms subsides 'out of reach' of erosion by the next sand-depositing storm.

The Seilacher (1982) model for forming and maintaining shelves, termed "storm grading" by Higgs (2004), does not apply to nearshore areas with high sediment supply, where the rate of deposition far outweighs the effects of occasional storm erosion (Seilacher, 1982). Thus, river-dominated deltas can prograde to the shelf edge relatively soon after a eustatic rise (see below).

To elaborate further on the Seilacher model, after a relative sea level rise (by subsidence or eustasy), if relative sea- or lake level is held constant for long enough, and if sedimentation outpaces subsidence, a shelf will build upward and outward at a certain equilibrium gradient (cf. Swift and Thorne, 1991, their fig. 2). The shelf edge builds out, past successive effective wave bases, eventually reaching SWBfm. Thereafter, the shelf can hypothetically continue to widen, but the advancing shelf edge cannot deepen further, potentially resulting in an essentially horizontal outer shelf. The time needed to build such a stillstand equilibrium profile reaching out as far as SWBfm must depend largely on: (1) the water depth following the initial relative rise; (2) the sedimentation rate; and (3) the depth of the local SWBfm, a function of storm-wave size. These remarks apply only to tectonically unconfined shelves like those on passive margins. On subduction continental margins (forearc basins), shelf build-out is structurally limited; if a shelf is present at all then the edge is structural, at the crest of the accretionary prism.

Storm grading allows surprisingly thick (100s-1000s m) shelf successions to accumulate. This can occur in two distinct settings: (A) on marine shelves with rapid subsidence (e.g., Covey, 1986), during time intervals uninterrupted by major, relative sea-level falls; and (B) in sea-level lakes (e.g. Quaternary Black Sea), where eustastic falls are curtailed by the lake sill, preventing forced exposure of the middle and outer shelf (Higgs, 1991, 2004).

In an alternative to the storm-grading model, Blum (2009) interpreted the modern continental shelf as an equilibrium *river* profile, graded to Quaternary glacioeustatic lowstand sea level. Conflicting with this model, modern passive-margin shelves can be steeper than the adjacent coastal plain, for example the Gulf of Mexico and Carolinas coasts of the United States (compare width between 0 m and 100 m land contours with that between 0 and 100 m isobaths; see also Gulf of Mexico coastal cross section in Blum, 2009). Instead, it is suggested here that today's continental shelves are storm-graded with respect to the last interglacial *high*stand, modified by falling-stage and lowstand erosion (submarine, subaerial), then planed by ravinement and drowned by the Holocene post-glacial rise.

Ramp Margins

Modern and ancient shelves that directly face deep water, here termed "open shelves", were called "shelf-break margins" by the Exxon group, as opposed to Exxon's "ramp margins", said to lack a shelf edge (Van Wagoner et al., 1988). However, the difference is merely a question of scale: a "ramp margin" is simply one half of the concave-up, transverse profile across a shallow-marine gulf or strait, which *does* have a shelf edge, at one or both ends, adjoining either a foreland-basin flysch trough or an ocean basin, potentially far away (100s-1,000s km). Three examples of such "closed shelves" (commonly referred to as epicontinental or epeiric seas), all in foreland basins, are the modern Taiwan Strait (Covey, 1986), modern Gulf of Carpentaria-Arafura Sea (e.g., Suter, 2006, fig. 4), and the Cretaceous Western Interior Seaway (WIS) of North America (e.g., Winn et al., 1987).

The ramp concept grew from early Exxon sequence-stratigraphic studies in Cretaceous strata of the WIS (e.g., Van Wagoner et al., 1988). These and subsequent studies were relatively local, compared to the transcontinental scale of the WIS, and they mainly considered east-west cross sections, sub-orthogonal to the seaway axis, giving the impression that a shelf edge was lacking. However, it is reasonable to assume a shelf edge at both ends of the seaway, where it met the Arctic Ocean and the Gulf of Mexico-Atlantic Ocean. The water depth of each shelf edge depended on the size of impinging oceanic storm waves (see above). Inward from each shelf edge, an equilibrium profile governed mainly by waves and tides would have ascended toward an interior submerged culmination in the WIS.

Effect of Eustasy

The Seilacher concept assumes stable relative sea- or lake level, i.e. stillstand. In reality, eustatic sea level constantly changes, at varying rates (Haq et al., 1987). Stillstand is achieved during highstand, but may be too brief to develop the full-length ("mature") equilibrium shelf profile, whether in an open or closed setting.

The envisaged effect of a eustatic cycle on an equilibrium shelf is as follows. A stillstand (highstand) equilibrium shelf is exposed by a eustatic fall, forming a fluvially incised coastal plain (Figure 3, stages 1-2). A subsequent, rapid rise drowns this coastal plain, forming an out-of-equilibrium, "overdeep" shelf (Stage 3; e.g., modern continental shelf). During the ensuing stillstand (highstand), a new, perched, shelf-and-slope equilibrium profile builds out, downlapping onto the overdeep shelf, producing a parasequence with clinoforms (Stages 4-5). The perched shelf is constructed with sediment supplied by an along-strike delta, including fair-weather mud fallout from hypopycnal plumes (redistributed as fluid mud during storms) and delta-derived, longshore-supplied, shoreface sand eroded by storm downwelling flows (Swift et al., 1983) and redeposited offshore as storm beds. This shoreface erosion ensures that the coastline advances more slowly than the shelf edge. In contrast, the (perched) delta itself progrades more rapidly across the overdeep shelf, reaching the "master" shelf edge much sooner than does the interdeltaic, perched shelf (e.g., Holocene Mississippi Delta). Shelf sand hyperpycnites and storm-wave-modified hyperpycnites (Higgs, 1990; Myrow et al., 2002; Pattison, 2005) are probably deposited on the (overdeep) prodelta and the advancing delta slope.

This simple model assumes that the perched shelf edge reaches the master shelf edge before sea level begins to fall. If not, the perched shelf undergoes regressive erosion by waves under the falling sea level (Plint, 1988), complicating the resulting parasequence architecture. It should be noted that the falling-stage systems tract model of Plint and Nummedal (2000), for ramp settings, applies to perched deltas rather than perched shelves (the entire high- and lowstand topset in their figure 1 is "coastal plain", abutting muddy clinoforms corresponding to the perched delta slope).

Supporting the model, shelf surveys in many parts of the world have revealed an inshore, Holocene, perched shelf-and-slope ("subaqueous delta" of Nittrouer et al., 1986), along strike from an adjacent perched delta (yet to reach the master shelf edge). Examples include the Amazon, Gulf of Papua, Yellow Sea, East China Sea and South China Sea open shelves (Nittrouer et al., 1986; Walsh et al., 2004; Liu et al., 2009), and the Adriatic closed shelf (Cattaneo et al., 2003; Pratson et al., 2004).

A succession of sea-level rises produces a stack (coset) of clinoform sets, individually variable in height and length. This coset forms the topset to a larger-scale clinoform set (cf. Brown and Fisher, 1977, fig. 4C), comprising the slope deposits of an adjacent deep-water body. Shelf clinoform height depends on, among other factors: (1) compaction; (2) pre-drowning water depth (nil, if exposed); (3) eustatic rise height; and (4) rise *duration*, the neglected element in sequence stratigraphy. The rise duration determines how much (additional) deepening takes place by subsidence, while the rising sea level traps sediment inshore, starving the shelf. For example, extreme clinoforms c. 400m high in the WIS (Lewis Shale; Winn et al., 1987) are interpreted here to reflect a eustatic rise that, though of modest magnitude (<50 m), was long-lived (c. 75 to 70 Ma; Miller et al., 2005). In this and another example, base-of-clinoform turbidites deposited below storm wave base (Winn et al., 1987; Plink-Björklund and Steel, 2004) can be interpreted as perched on a drowned, former equilibrium shelf surface.

Sequence-Stratigraphic Implications Important for Exploration

The parochial view of ramps as being unrelated to shelves led to a decades-old misconception in sequence stratigraphy: Type 1 sequences on shelves are said to differ fundamentally from those on ramps, the latter supposedly having no shelf edge beyond which the shoreline can pass if eustatic sea level falls low enough (Van Wagoner et al., 1988, figs 2, 3). In fact, both have a shelf edge; therefore, Type 1 sequences have the same architecture in both settings, assuming the same sea-level fall magnitude and shelf-edge water depths. Type-1 sequences on "ramps" are simply the proximal part of those on "shelves", i.e., the shelf-edge LST is far away (Van Wagoner et al., 1988, figs 2, 3). Thus, instead of the classical subdivision of sequences into Type 2 (later abandoned; Posamentier and Allen, 1999) and Type 1, with the latter subdivided into "shelf" and "ramp" variants, one need only distinguish between (A) sequences that encroach beyond the shelf edge, due to a large eustatic fall, for which the name "Shelf-Edge Sequences" is proposed, and (B) "Suprashelf Sequences" that do not.

Modern and ancient closed shelves tend to have a lower equilibrium-profile gradient (axially) than open shelves, as their axial length commonly far exceeds the cross-shelf width of open shelves (e.g., modern North Sea and Hudson Bay closed shelves). Thus, lowstand non-incised rivers, formed in place of incised valleys if the eustatic fall does not pass the shelf edge and the exposed sea-floor gradient is relatively low (Posamentier, 2001), are predicted here to be more common on closed shelves. Indeed, the type succession for shelf deposits containing non-incised rivers is the Mio-Pleistocene of the Java Sea (Posamentier, 2001), a closed shelf.

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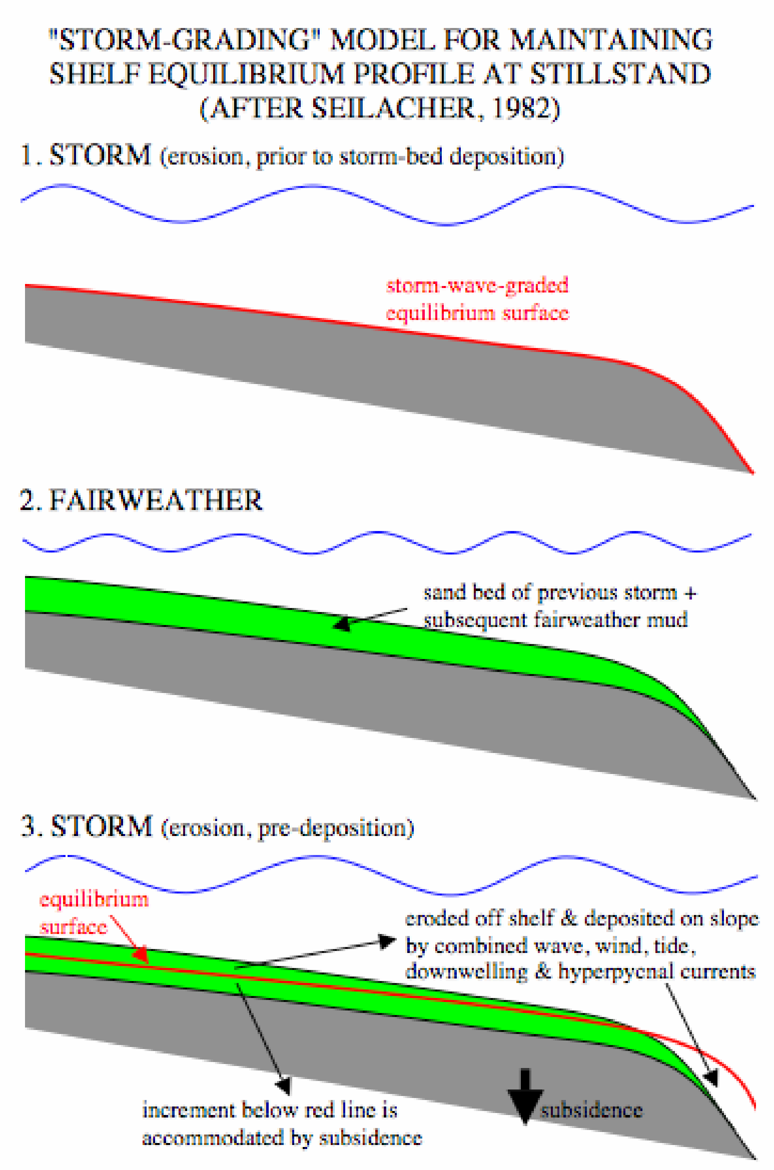

Figure 1. "Storm-grading" model, amplified after Seilacher (1982), for maintaining an equilibrium shelf profile, thereby preventing subaerial emergence. Assumes an interdeltaic position and sea-level stillstand.

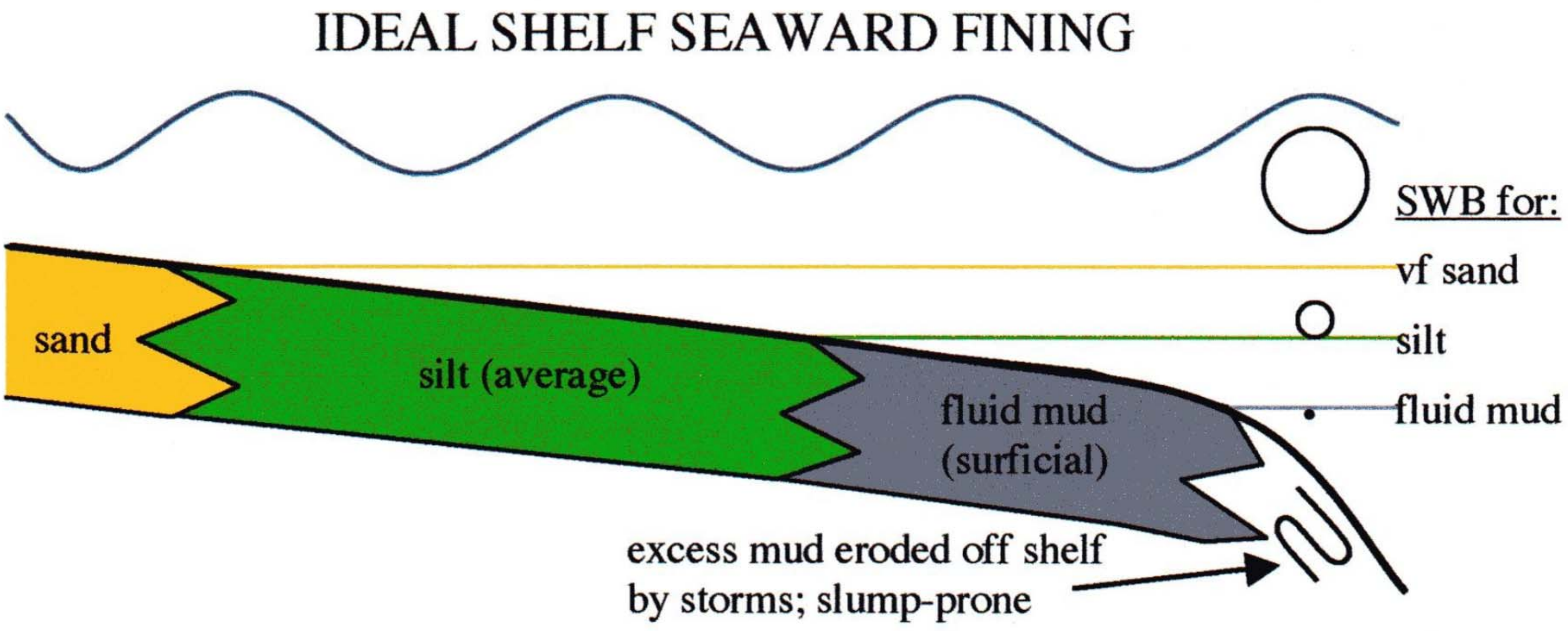

Figure 2. Model for seaward fining on an ideal shelf. The decrease in storm-wave seabed power with increasing water depth governs the maximum grain size remobilizable at any point. Thus, each grain size has its own storm wave base (SWB), toward which it moves incrementally in successive storms ("progressive sorting" of Swift and Thorne, 1991). Even the mud consists mostly of storm beds. See text for further explanation.

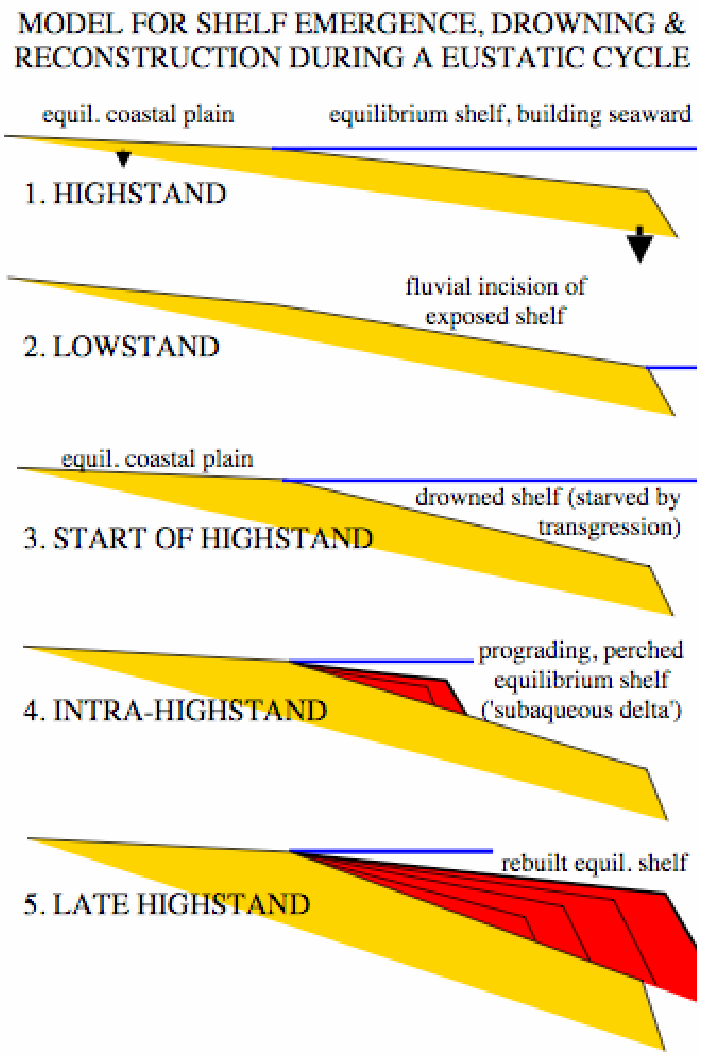

Figure 3. Model for a eustatic cycle of shelf growth (highstand), exposure (lowstand), drowning (transgression) and regrowth (highstand). Assumptions: (1) inter-deltaic position; and (2) seaward-increasing subsidence (compaction & tectonic; i.e. passive margin or foreland basin cratonward flank), hence the initial shelf steepens with time (stages 1 to 5).