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Responses of River Deltas to Sea-Level and Supply Forcing: Autostratigraphic View

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1. Introduction

A long-standing geological notion that dates back to Huttonian theory of the late 18th century (Schlager, 1993) suggests that (1) there can exist a balanced state between the effect of relative sea level rise and the effect of sediment supply to the depositional system, for example evidenced by coastal aggradation and a vertical shoreline trajectory, and that (2) regression and transgression reflect imbalances between the two primary drivers: i.e. regression when sediment supply dominates sea level rise, and transgression when sea level rise dominates sediment supply (Fig. 1A). More specifically, it has been taken as axiomatic that given steady external forcing by constant sediment supply (rate Q_S) and constant relative sea level rise (rate R_{slr}), a river delta grows to achieve an equilibrium configuration, produces a particular sediment-stacking pattern and maintains a constant rate of shoreline migration in a particular direction (Weller, 1960; Van Andel & Curray, 1960; Sloss, 1962; Curray, 1964; Swift, 1968; Swift et al., 1971; Curtis, 1970; Vail et al., 1977; Mitchum et al. 1977; Brown & Fisher, 1977; Posamentier et al., 1988; Galloway, 1989; Swift & Thorne, 1991; Shanley & McCabe, 1994; Stanley & Warne, 1994; Myers & Milton, 1996; Neal & Abreu, 2009). We refer to this mode of stratigraphic response as *equilibrium response*, by which steady external forcing results in steady stratigraphic pattern of deposition.

Autostratigraphy, a fairly new arrival in the field of geology, suggests that this presumed mode of stratigraphic response does not hold true in general, but instead that (1) even with steady forcing, river deltas generally fail to sustain a constant and uniform stratigraphic pattern of deposition (Fig. 1B), and (2) unsteady forcing can result in uniform stratigraphic configuration. Exploring such *nonequilibrium responses* (see below) is essential if we are to elucidate the complex stratigraphy that river deltas produce at different time scales. Introducing principles of autostratigraphy and related basic notions, the present chapter outlines these recent discoveries and gives a synthetic understanding of the origin of regression and transgression and of aggradation and degradation in deltaic settings.

2. Deterministic autogenesis

Autogenesis has conventionally been associated with responses that are local (a small part of the system), stochastic and cyclic, such as typically illustrated with river avulsion or delta-lobe switching. There is also another type of autogenesis that is global (i.e. the entire system), deterministic and non-cyclic, as has been noticed recently (Fig. 2). A primary aim of autostratigraphy is to explore the latter and their stratigraphic responses, thereafter to identify allogenic stratigraphic products and responsible unsteady dynamic external forcing. Although stratigraphic records are generally composed of both autogenic and allogenic products, conventional stratigraphy has been apt to ignore the importance of autogenesis and thus to overrate allogenic processes.

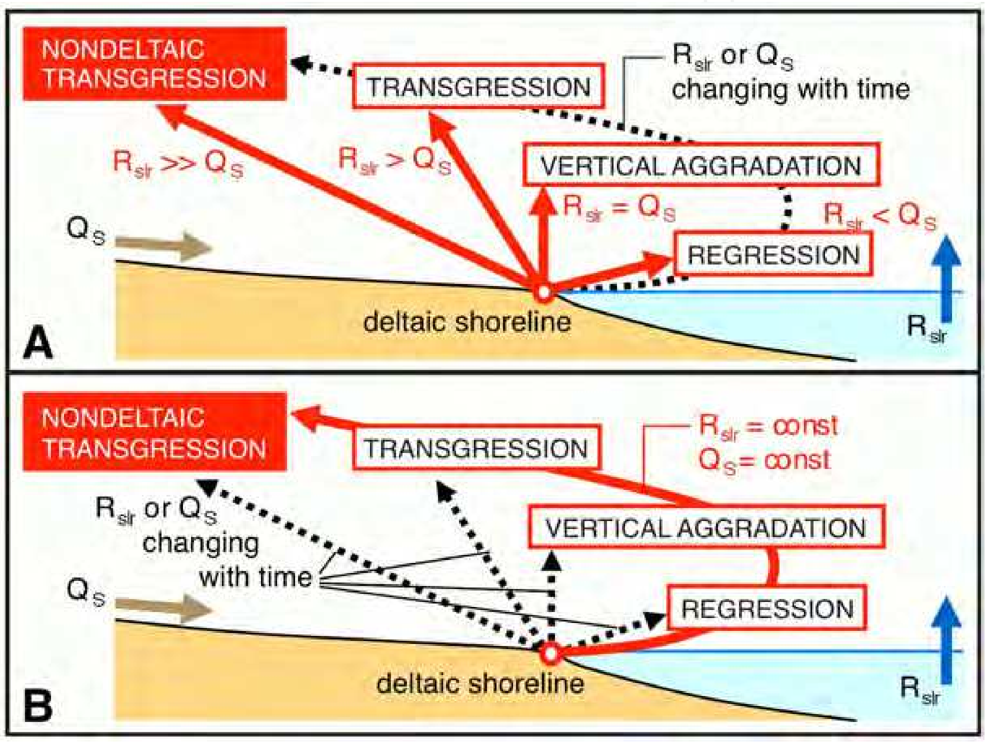

Fig. 1. Two different views of the origin of regression and transgression during relative sea level rise. (A) Conventional geology of river deltas, inherently based on the recognition of equilibrium response, suggests that there exists a balanced state between the effect of relative sea level rise (rate R_{slr}) and the effect of sediment supply (rate Q_S), and that given magnitudes of the two factors, the shoreline migrates at a constant rate in a particular direction. (B) A new view, provided by autostratigraphy, claims that regression, vertical aggradation and deltaic transgression all reflect transient states of a river delta that given enough time must become a nondeltaic transgressive system. Such a shoreline trajectory curve as shown in the diagram has conventionally been attributed to temporal change in R_{slr} or Q_S rather than nonequilibrium response. According to the new viewpoint advocated here, the constant linear shoreline trajectories shown in (A) must be due to unsteady dynamic forcing.

The concept of *deterministic autogenesis* (Muto & Steel, 2002a; formally defined by Paola et al., 2009) has given rise to innovative thinking in regard to the geology of river deltas. This new concept applied to, for example, typical regressive-transgressive/flooding successions such as those shown in Fig. 3A, illustrates that such successions can form solely as autogenic

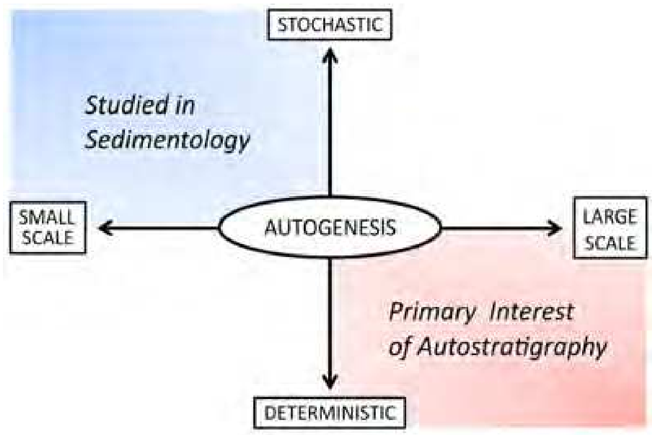

Fig. 2. A conceptual division of the entire field of autogenesis in terms of whether it is on large-scale or small-scale and whether stochastic or deterministic. The primary interest of autostratigraphy is to explore large-scale and deterministic autogenesis, whereas small-scale and stochastic autogenesis has been well studied in conventional sedimentology.

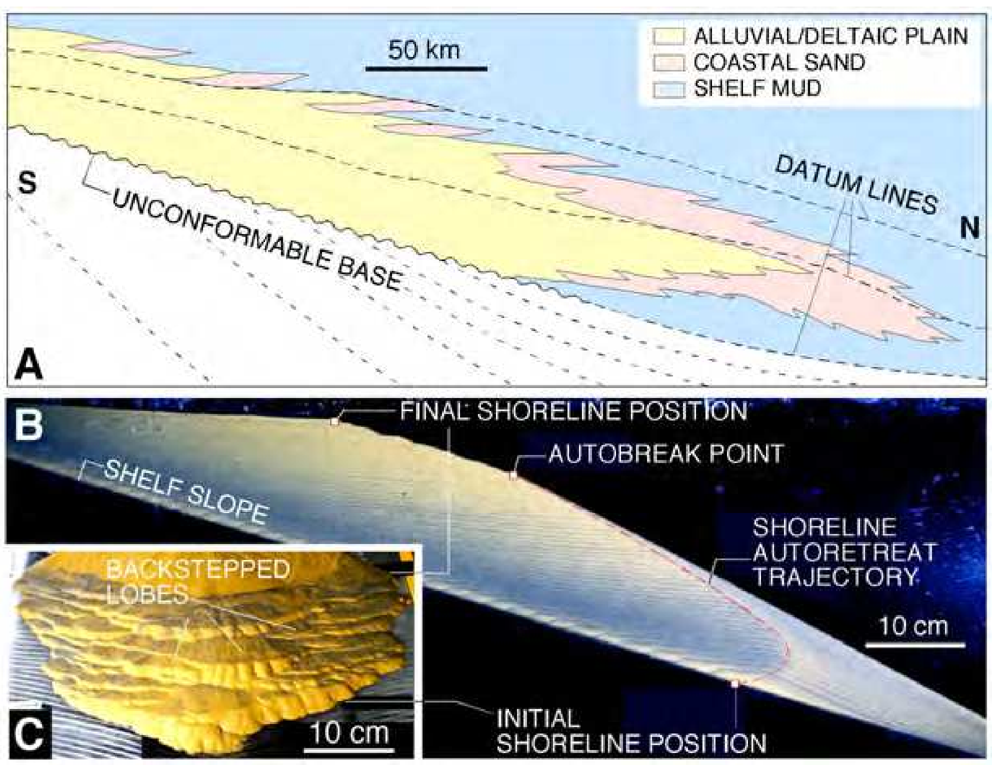

Fig. 3. (A) Schematic N-S cross-section through the Middle Jurassic Brent Delta, northern North Sea, showing an overall regressive-transgressive succession associated with back-stepping delta lobes. Simplified from Graue et al. (1987). (B) Longitudinal profile of a delta that was built during an experimental run conducted with constant rates of sediment supply and sea-level rise. See Muto (2001) for details of the experiments. Note that the stratigraphic architecture of the Brent Delta is similar to a significant degree to that of the experimental delta. (C) Repeated stochastic autogenesis (lobe switching) interacts with longer term deterministic autogenesis to form the details of the shoreline migration pattern reflected in the "shazzam" facies boundaries of (A). From Muto & Steel (2001).

responses to steady rise of relative sea level (e.g. constant subsidence without eustatic fluctuation) in conjunction with steady sediment supply, a result that is reproducible in flume/tank experiments (Fig. 3B; Muto, 2001). Consideration of the various forms of such deterministic autogenic behavior that may be manifested in nature leads us to believe that many existing stratigraphic studies on river deltas require thorough re-examination in light of this new perspective. In the following sections we argue the impact of deterministic autogenesis on the interpretation of stratigraphy, and as a result, strongly suggest that the science of river deltas currently stands at a crossroads for further major advances.

3. External forcing and stratigraphic responses

Conventional understanding of river deltas inherently relies on the assumption that equilibrium response holds true in general, and consequently is apt to favor the interpretation that any large-scale facies break or change in the stratigraphic pattern within a deltaic succession reflects unsteady external forcing such as temporal changes in R_{slr} or Q_S (*allogenic general response*). However, equilibrium response is not the only response to steady forcing, nor even necessarily the expected response. Theoretically, there are two other modes of stratigraphic response in such a cause-and-effect relationship. These are *autogenic nonequilibrium response* (unsteady stratigraphic configuration caused by steady forcing) and *allogenic nonequilibrium response* (steady stratigraphic configuration maintained by unsteady forcing) (Fig. 4). Nonequilibrium responses essentially arise from downstream transformation of the sediment-supply signal from constant to variable due to systematic deposition and erosion along the path of transport. Unfortunately, stratigraphic interpretation of equilibrium response can often be flawed due to a failure to appropriately consider nonequilibrium responses.

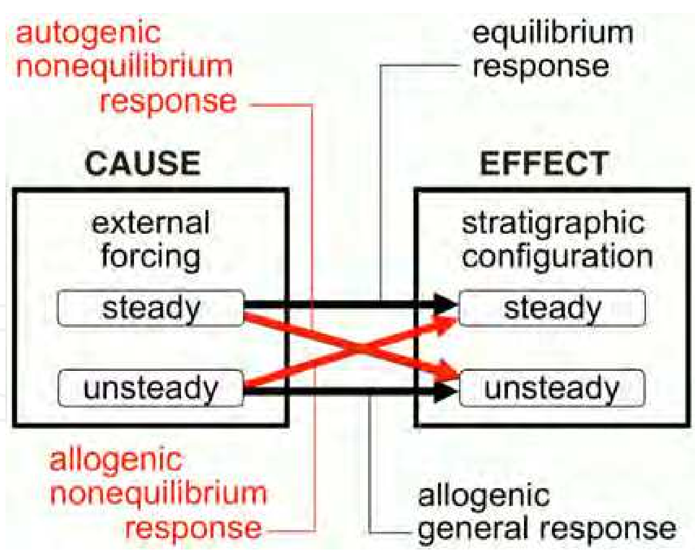

Fig. 4. Stratigraphic response of a depositional system to external forcing. From the viewpoint of a cause-and-effect relationship, we can imagine four different modes of stratigraphic response: *equilibrium response* (steady stratigraphic configuration by steady forcing), *autogenic nonequilibrium response* (unsteady stratigraphic configuration by steady forcing), *allogenic nonequilibrium response* (steady stratigraphic configuration by unsteady forcing), and *allogenic general response* (unsteady stratigraphic configuration by unsteady forcing). The importance of nonequilibrium responses has only recently become widely recognized in the geological community.

New insight into the problem has been obtained via experimental research on stratigraphy in general (Paola et al., 2009), as well as numerical (Muto & Steel, 1992; Milton & Bertram, 1995; Ritchie et al., 1999; Swenson et al., 2000; Parker et al., 2008a) and experimental research (Paola, 2001; Muto, 2001; Muto & Steel, 2001, 2004; Kim et al., 2009) that specifically addresses the question of how river deltas react to steady and unsteady forcing. This work, when combined with site-specific field application (Muto & Steel, 2002a; Parker et al., 2008b), provides a view of the problem that differs rather markedly from the conventional model in three ways. First, although equilibrium response is possible, it is restricted to very specific conditions which are rare in natural systems (Muto & Swenson, 2006). Second, steady sea-level forcing is much more likely to generate autogenic nonequilibrium response than equilibrium response (Swenson & Muto, 2007). Third, deltaic systems can have different stratigraphic responses to the same external forcing depending on geomorphic conditions (Petter & Muto, 2008).

A long-standing geological notion suggests that steady external forcing results in a steady stratigraphic pattern of deposition (equilibrium response; Fig. 4), and that this mode of stratigraphic response is true in general. Prior to the recognition of nonequilibrium responses, any large-scale unsteady stratigraphic features were attributed to unsteady external forcing (i.e. allogenic general response). Autostratigraphy suggests that unsteady stratigraphic configuration can be caused by steady forcing (autogenic nonequilibrium response) and steady stratigraphic configuration can be maintained by unsteady forcing (allogenic nonequilibrium responses).

4. Regression and transgression as nonequilibrium responses

The nonequilibrium view of river deltas, along with the idea of deterministic autogenesis, has led to the following understanding of regression and transgression, two of the basic building blocks of stratigraphy. With constant R_{slr} (>0) and constant Q_S (>0), it is inevitable that a river delta initially experiencing regressive growth must eventually turn around into a transgressive mode, which is referred to as *autoretreat* (Muto & Steel, 1992; Swenson et al., 2000). After the onset of shoreline transgression, the subaqueous slope of the delta (foreset) may continue to accrete for some time. As sea level rise continues, however, the delta inevitably meets a critical event (*autobreak*; Fig. 3B) in which sediment supply to the delta front eventually drops to zero, the delta foreset is abandoned, and the shoreline undergoes rapid transgression by drowning (Muto, 2001; Parker et al., 2008a). After this time, the depositional system is no longer deltaic because sediment is not delivered beyond the shoreline, but has instead become an estuary (*sensu* Darlymple, 1992). In fact, the stratigraphic record is full of flooding events similar to those that arise in response to autobreak (e.g. Fig. 3A). These flooding events, usually defining parasequences in sequence stratigraphy, need not be due to eustatic fluctuation but rather may arise naturally either from deterministic autogenesis in response to steady subsidence (R_{slr} = const) or stochastic autogenesis (e.g. channel avulsion), or a combination of the two (Muto & Steel, 2001; Fig. 3C).

The primary causes for this nonequilibrium response to steady sea level rise are (1) progressive expansion of the river delta both basinwards and laterally due to continuing sediment supply, but with increasing tendency for the sediment to deposit landward of the shoreline, and (2) continuing rise in relative sea level. Suppose that R_{slr} and Q_S are kept constant with time. Cumulative sea level elevation increases with time, whereas the aggradation rate of the delta averaged over the entire surface area progressively decreases as t^{-n}, where t denotes time and n can vary between 2 and 3. Because of this behavior, a prograding delta is intrinsically unable to sustain a constant response to steady sea level rise. For the depositional system to maintain its original progradation as a delta, it would be necessary for Q_S or R_{slr} to change in a specific manner with time. This, by definition, would lead to an allogenic nonequilibrium response. Any river delta subjected to steady sea level rise cannot therefore sustain a particular depositional style indefinitely, but will inevitably experience a nonequilibrium response. If sea level rise continues for a sufficiently long duration, the river shoreline may become nondeltaic, for example the upstream end of an estuary or drowned valley. The magnitude of R_{slr} relative to Q_S does play an important role, as these parameters can be used to characterize intrinsic length and time scales of the river delta such that the nonequilibrium response is delayed or hastened. Under conditions of the same constant sea level rise, a small depositional system fed with low Q_S will experience transgression and become an estuary in a shorter time, whereas a larger system fed with high Q_S will maintain a regressive delta behavior for a longer period of time before transgression and drowning (Parker et al., 2008b). Since both of the afore-mentioned systems can be coeval, there is thus little basis for correlating a particular deltaic stratigraphic pattern to a particular segment of a sinusoidal curve of sea level change. For example, the Sabine and Trinity Rivers became nondeltaic (estuarine) during the Postglacial sea-level rise, while less than 100 km to the west, the Colorado and Brazos Rivers deposited a succession of backstepping delta lobes during the same period (Anderson et al., 1996).

The autogenic nonequilibrium response of a delta displays variation depending upon the initial downstream length of their feeder alluvial river(s) (as measured from e.g. a bedrock-alluvial transition point). There exists a critical magnitude of alluvial length (L_{crt}) for which, given R_{slr}, Q_S is precisely as large as required to maintain aggradation over the entire length of the existing alluvial reach of the river (Tomer et al., 2011). In case a pre-existing alluvial length exceeds L_{crt}, the shoreline abruptly migrates landward at the onset of sea level rise as an estuary rather than a delta. This is because under such conditions Q_S is no longer sufficient to cover the entire length of the existing alluvial river, and thus no river sediment reaches the shoreline (i.e., substantially the same as autobreak). Such nondeltaic transgression is expected to proceed very rapidly initially, but subsequently decelerate as the alluvial length approaches L_{crt}. Even though R_{slr} and Q_S are held constant, the shoreline inevitably follows a concave-upward trajectory as a manifestation of the nonequilibrium response. Fig. 5 shows shoreline trajectories estimated with the autoretreat-autobreak model (Muto, 2001) for five natural rivers (Fly, Mekong, Mississippi, Brahmaputra and Ebro) during Postglacial sea level rise, on the assumption that (1) prior to sea level rise, they had extended to the present shelf edge or thereabouts and built deltas there, (2) Q_S was constant but different for each river, (3) R_{slr} was significantly decreased, or became zero, around 8–6 kaBP, and (4) the shoreline passed through reference points that are specified based on separate evidence from published literature. The simulation suggests that every one of the five alluvial systems became nondeltaic and transgressive as soon as the sea level began to rise. This is because each of the Glacial lowstand river systems built such an alluvial reach with length that far exceeded L_{crt}, prior to sea level rise. In the case of the Fly River during Postglacial sea level rise, for example, L_{crt} is estimated to have been 24 km. Nevertheless the river had extended over 900 km to the shelf edge before sea level started to rise. Evidence for intense transgression associated with this “overextension” can be found in the modern Fly system, which appears to be in a recovery process of deltaic sedimentation starting from when sea level rise decelerated (Parker et al., 2008b). Each modeled system possesses a unique shoreline trajectory despite similar relative sea-level histories.

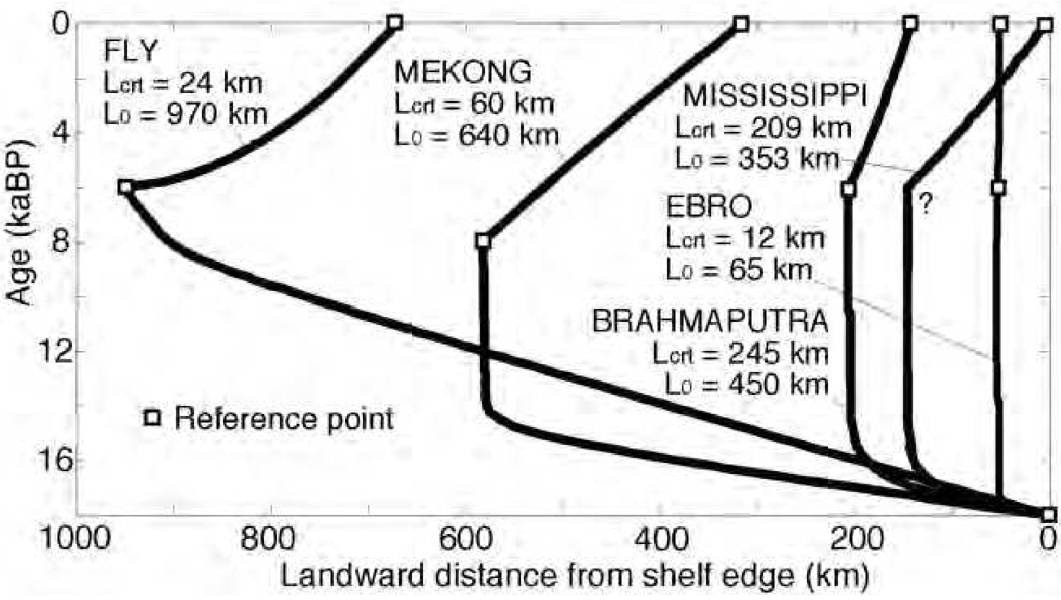

Fig. 5. Shoreline trajectories estimated via numerical simulation based on the autoretreat-autobreak geometrical model of Muto (2001). Relevant assumptions are as follows: (1) prior to sea level rise, the rivers had extended to present shelf edge positions or thereabouts and built deltas there, (2) Q_S was constant but unique to each river, (3) R_{slr} was also unique to each river, but significantly decelerated around 8-6 kaBP in each case, according to the characteristics of that case, and (4) the shoreline migrated via reference points that can be specified with separate evidence. The reference points and/or related data were adopted from information in Parker et al. (2008b) for the Fly River; Coleman et al. (1998), Harmar & Clifford (2007) for the Mississippi River; Tamura et al. (2009), Liu et al. (2009), Xue et al. (2010) for the Mekong River; Somoza et al. (1998), Rovira & Ibanez (2007) for the Ebro River; and Goodbred & Kuehl (2000), Goodbed et al. (2003), Mikhailov and Dotsenko (2006), Liu et al. (2009) for the Ganges-Brahmaputra River system. Note that the L_{crt} and L_0 values are not related to the scale at the distance from shelf edge.

5. Aggradation, degradation and grade during falling sea level

Aggradation and degradation of river deltas with falling sea level is another fundamental issue comparable to the question of regression and transgression with rising sea level. It is well documented that both aggradation and degradation of river deltas can take place during sea-level fall (Schumm, 1993; Blum & Törnqvist, 2000; Van Heijst & Postma, 2001; Browne & Naish, 2003; Strong & Paola, 2008). However, the rationale for this apparent complexity of behavior remains partially obscure. Recent physical experiments (Muto & Steel, 2004; Swenson & Muto, 2007; Petter & Muto, 2008) suggest that nonequilibrium response can account for some of this behavior in a straightforward way.

An understanding of the stratigraphic response of river deltas to falling sea level requires a clarification of the concept of *grade*, the state of a river at which neither net deposition nor net erosion take place in spite of continuing sediment supply. Grade therefore precisely defines the critical condition discriminating between aggradational and degradational river systems. This concept, originally advocated by G. K. Gilbert in the late 19th century, is often presented as the consequence of long-term equilibrium response of a river system subject to stationary sea level. Common beliefs based on equilibrium response (Thorne & Swift, 1991; Holbrook et al., 2006) are that (1) alluvial rivers in deltaic settings aggrade in response to sea-level rise and degrade in response to sea-level fall, (2) as long as sea level remains stationary, the rivers eventually become graded, and thus (3) grade represents the equilibrium configuration of an alluvial river under conditions of stationary sea level.

Such conceptual models of graded rivers downplay the fate of the sediment bypassed through the "graded" reach, and in particular, how its sequestration in the deltaic environment affects the dynamics of the attached river system. However, if sea level remains stationary, rivers continue to aggrade in response to delta progradation, and consequently never attain grade. Model experiments to examine the dynamics of the downstream and upstream boundaries of alluvial rivers building deltas have shown that alluvial grade is physically possible only under rather specific conditions pertaining solely to sea-level fall (Jordan & Flemings, 1991; Nummedal et al., 1993; Leeder & Stewart, 1996; Muto & Swenson, 2005). Alluvial grade arises in two distinct ways depending on geomorphic conditions and characteristics of sea-level fall, for which alluvial slope S_a and basin slope S_b are particularly influential (Figs. 6, 7). Where $S_a < S_b$, alluvial grade is attained and sustained by allogenic nonequilibrium response through a particular style of decelerating sea-level fall (Muto & Swenson, 2005). If sea level instead falls at a constant rate in this geomorphic setting, the river aggrades at an early stage but later degrades by autogenic nonequilibrium response (Swenson & Muto, 2007). Where $S_a = S_b$, alluvial grade is attained by equilibrium response at any constant rate of sea level fall (Muto & Swenson, 2006). Where $S_a > S_b$, grade is never attained, and the alluvial system simply continues to aggrade during sea level fall and the alluvial river finally detaches from the receding shoreline, so that the depositional system becomes nondeltaic via autogenic nonequilibrium response (Petter & Muto, 2008). Thus, aggradational river deltas tend to undergo autogenic nonequilibrium response to constant sea-level fall whereby they eventually become nondeltaic ($S_a > S_b$) or degradational ($S_a < S_b$). Thus, rivers building deltas, in general, cannot maintain a particular growth style for prolonged periods of time, during either sea-level rise or fall, and the manner in which sediment is distributed across a basin depends heavily upon the geomorphic conditions of the alluvial river and basin (Figs. 6, 7).

6. Timescales

Most present-day large deltas have existed through the past 50–60 Ma. However, during this time they have continually evolved and changed at much shorter time scales (i.e. the autogenic focus of the present argument). Whereas stochastic autogenic responses in river-delta systems (not discussed in this work) are commonplace at very short timescales (0.1-1 ka), deterministic autogenic responses require a longer time and minimum basin length. Deterministic autogenic responses involving cross-shelf regression and wholesale retreat of deltaic complexes have been shown to operate at shelf-transit time scales of 50-200 ka (Burgess & Hovius, 1998; Muto & Steel, 2002b; Carvajal & Steel, 2006; Steel et al., 2008). Quaternary eustatic sea-level curves show 10–20 m amplitude changes at ka-cyclicity over interglacial-to-glacial eustatic fall intervals of 10–100 ka duration (e.g. Stages 4–2; Lambeck et al., 2002), though Holocene sea-level rise was relatively steady over a period as long as 15 ka. Past greenhouse climate conditions would likely have yielded more prolonged periods of sea-level stability. Short allogenic cycles do not give river deltas sufficient time to adjust to the changes in boundary conditions, and therefore cannot be expected to significantly change the autogenic response of a system. Likewise, low-magnitude allogenic forcing may not alter the boundary conditions sufficiently to deter autogenic response. The following questions therefore remain outstanding: 1) do allogenic boundary conditions remain stable for long enough periods to allow deterministic autogenic responses to run their course; and 2) what are the threshold amplitudes and frequencies of perturbations in allogenic boundary conditions of river deltas that are sufficient to interrupt these responses? These questions have implications for paleo-environmental interpretation of the stratigraphic record as well as for predicting the long-term fate of modern river deltas under the effect of climatic change and human impact (Ericson et al., 2006; Kim et al., 2009; Syvitski et al., 2009).

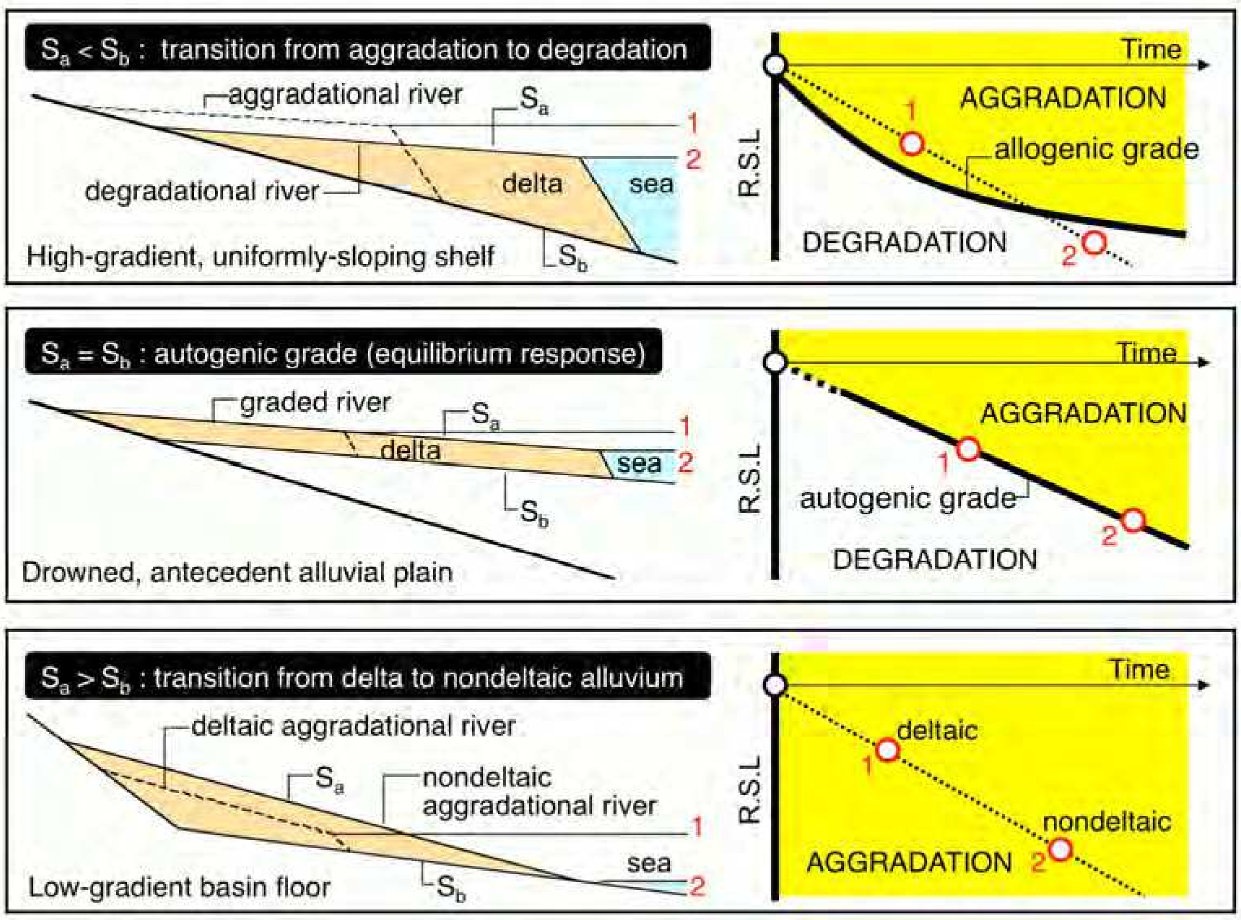

Fig. 6. Autostratigraphic view of alluvial aggradation and degradation during sea level fall. Alluvial grade is physically possible but can be attained and sustained only during sea level fall unless the river delta has a fixed downstream boundary. Patterns of sea level fall that allow the attainment of grade depend on geomorphic conditions of the deltaic system (alluvial slope S_a and basin slope S_b, particularly). Where $S_a < S_b$, alluvial grade can be attained and sustained only with sea level fall of a particular decelerative pattern. If sea level drops at a constant rate in this geomorphic condition, the feeder alluvial system aggrades in the early stage, but with enough time inevitably becomes degradational. Where $S_a = S_b$, a river delta steadily progrades and sustains grade autogenically only during constant sea level fall. Where $S_a > S_b$, the feeder alluvial system never attains grade, but instead continues to aggrade, so evolving from a deltaic system to a nondeltaic system as long as sea level continues to fall.

Fig. 7. Experimental illustration of the three types of autogenic nonequilibrium response to constant sea level fall depending upon geomorphic conditions. The upper and lower images represent states 1 and 2, respectively, of the same geomorphic conditions in Fig. 6. Note that different river/basement slope relationships can give rise to different patterns of response of the systems to constant sea-level fall. Photos adopted from Muto & Steel (2004) and Petter & Muto (2008).

7. How can autogenic and allogenic response be distinguished in the stratigraphic record?

Long-term stratigraphy encapsulates the composite signal of both autogenic and allogenic responses. However, the intrinsic nature of autogenic responses makes them a constant and predictable signal in the stratigraphic record, and therefore, allogenic responses should be interpreted only after the autogenic framework has been established. How should this be done?

The dependence of nonequilibrium response upon the shape of the basin and depositional surface is such that it can be easily simulated using geometric models (Paola, 2000; Muto et al., 2007; Petter et al., 2011). This requires input concerning basement and fluviodeltaic gradients, as well as rates of sea-level change and sediment supply. Comparison of the modeled shoreline trajectory with observed trajectories allows the identification of deviations from autogenic nonequilibrium response (Muto & Steel, 2002a; Petter et al., 2010; Wolinsky et al., 2011). Trajectories resulting from this response are recognized as smooth, concave-up or concave-down curves indicative of decelerating progradation as the system expands through time. At each point of deviation from the predicted trajectory, a general allogenic response is interpreted, and the geometric model can be reset to new boundary conditions at this point. Successive breaks in boundary conditions due to paleo-environmental changes are thus reconstructed by repeated application of this procedure. The parameters required for modeling are readily interpreted from regional geologic datasets (Petter et al., 2011).

8. River deltas and their stratigraphy

River deltas constitute the single most important agent delivering clastic sediment from land to sea. They drive the sedimentary growth of continental margins and fill basins of various types. The recognition of nonequilibrium responses in the development of coastal stratigraphy has given rise to a new framework of genetic stratigraphy, autostratigraphy (Muto et al., 2007), that encompasses both equilibrium and nonequilibrium responses, and takes full account of both steady and unsteady external forcing. Autostratigraphic responses in river deltas tend to prevent any prolonged continuity of particular growth styles, whether during rising or falling sea level forcing. It has also become increasingly clear that nonequilibrium response plays a key role in the variety of observed shoreline stacking patterns (Kim et al., 2006). Consequently, changes in R_{slr} or Q_S condition need not be interpreted based on the presence of certain stacking patterns, and said stacking patterns do not necessarily predict subsequent stacking patterns (e.g. Neal & Abreu, 2009) since they are not manifestations of allogenic response. The stratigraphic record of river deltas therefore reflects the extent to which nonequilibrium behavior proceeds between periodic changes in boundary conditions caused by external forcing (i.e. tectonic, climatic, or eustatic events). Stratigraphic interpretation of coastal plain and shallow-marine strata should be conducted with an acute awareness of the intrinsic intermittent character of river-delta growth style.

9. Conclusion

Recent developments in experimental stratigraphy and geomorphology have cast doubt on a long-standing principal theorem in geology, i.e. that given steady external forcing by constant sediment supply and constant relative sea level change, a river delta grows to achieve an equilibrium configuration and produces a particular sediment-stacking pattern. A new, alternative view that is provided by autostratigraphy tells that (1) even with steady forcing, river deltas generally fail to sustain a constant and uniform stratigraphic pattern of deposition due to their inherent deterministic autogenesis, and (2) unsteady forcing can result in uniform stratigraphic configuration. Exploring such nonequilibrium response is essential if we are to elucidate the complex stratigraphy that river deltas produce at different time scales. This ongoing change in how we view river deltas and their stratal products brings a whole new understanding of the origin of regression and transgression and of aggradation and degradation in deltaic settings.

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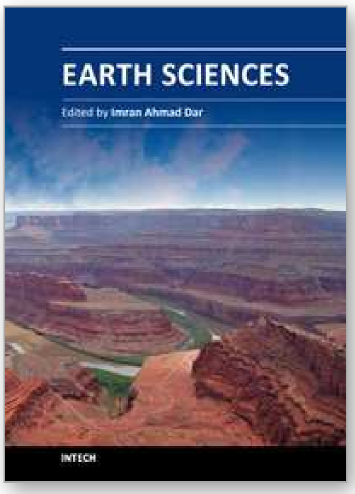

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The studies of Earth's history and of the physical and chemical properties of the substances that make up our planet, are of great significance to our understanding both of its past and its future. The geological and other environmental processes on Earth and the composition of the planet are of vital importance in locating and harnessing its resources. This book is primarily written for research scholars, geologists, civil engineers, mining engineers, and environmentalists. Hopefully the text will be used by students, and it will continue to be of value to them throughout their subsequent professional and research careers. This does not mean to infer that the book was written solely or mainly with the student in mind. Indeed from the point of view of the researcher in Earth and Environmental Science it could be argued that this text contains more detail than he will require in his initial studies or research.