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The intrinsic rarity of equilibrium response in stratigraphic processes

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A R T I C L E I N F O

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A B S T R A C T

Conventional sequence stratigraphy is based, explicitly or implicitly, on the hypothesis that steady external forcing results in a steady stratigraphic configuration (equilibrium response), so that an unsteady stratigraphic configuration is usually believed to result from unsteady external forcing. Recent advances in autostratigraphy, on the other hand, have led to a significantly different notion that steady external forcing generally results in an unsteady stratigraphic configuration (non-equilibrium response). To advance this debate, it is necessary to clarify what exactly is meant by a steady stratigraphic configuration. Here, we propose a quantitative criterion for defining the latter concept in terms of the straightness of the shoreline trajectory, and specifically a straight shoreline trajectory or the shoreline being held still as a sign to express steady stratigraphic configurations. In such a definition, a steady stratigraphic configuration means that the ratio of the rate of aggradation and the rate of progradation is constant, or one of these two rates is zero. Based on this criterion, a total of 7 types of steady stratigraphic configurations can be clarified, most of which require unsteady external forcing and are thus realized by non-equilibrium response, although special cases exist. The reason that non-equilibrium responses dominate the stacking of strata is that it is common for a growing basin-margin depositional system to change its surface area. The size-changing system will easily change the stacking pattern (unsteady stratigraphic configuration) if the external forcing is steady, or, if the steady stratigraphic configuration is maintained, the rate of external forcing must change in a particular pattern (unsteady external forcing). Equilibrium responses can occur, but in very special cases. Conventional sequence stratigraphy should take into account the importance of non-equilibrium response.

1. Introduction

Deciphering the relationship between sediment stacking patterns and responsible external forcing, such as eustatic changes, tectonic activities, and sediment supply, is the key to genetic stratigraphy. During the last three decades, the development of autostratigraphy has updated the conventional view of how a depositional system responds stratigraphically to external forcing (Muto et al., 2007). By taking full account of large-scale autogenic changes of the depositional systems, autostratigraphy sheds light on the stability of stratigraphic configuration in response to steady or unsteady changes of external forcing.

From a formal-logical point of view, there can be four different types of stratigraphic response (Fig. 1). The first one is named equilibrium response, a type of stratigraphic response by which steady external forcing results in a steady stratigraphic configuration (i.e., steady-to-steady correspondence). As a corollary of equilibrium response, unsteady dynamic external forcing may produce unsteady stratigraphic configuration (i.e., unsteady-to-unsteady correspondence) (Fig. 1a). There is also non-equilibrium response, which is opposite to equilibrium response. Two types of non-equilibrium response can be classified (Fig. 1b), i.e., steady external forcing results in unsteady stratigraphic configuration (i.e., steady-to-unsteady correspondence), and unsteady external forcing results in steady stratigraphic configuration (i.e., unsteady-to-steady correspondence).

A fundamental idea in autostratigraphy is that given steady external forcing, the depositional system generally takes non-equilibrium responses, rather than equilibrium responses as implicitly or explicitly believed in conventional sequence stratigraphy (e.g., the A/S ratio concept) (Jervey, 1988). Equilibrium responses are physically possible, but can only be realized under special

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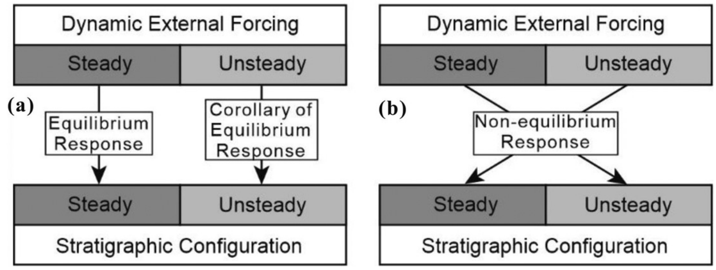

Fig. 1. Stratigraphic responses of depositional systems to dynamic external forcing. (a) The concept of equilibrium response, by which steady dynamic external forcing produces steady stratigraphic configurations, and thus unsteady stratigraphic configuration is commonly attributed to unsteady dynamic external forcing. (b) The concept of non-equilibrium response, by which steady dynamic external forcing causes not only steady stratigraphic configurations but also unsteady stratigraphic configurations, and unsteady dynamic external forcing can cause steady stratigraphic configurations. Non-equilibrium response is not considered in conventional sequence stratigraphy, whereas autostratigraphy incorporates both equilibrium and non-equilibrium responses (after Muto et al., 2016b).

conditions. The rarity of equilibrium response has so far been strongly supported by physical and numerical experiments (Muto and Swenson, 2006; Muto et al., 2016a; Wang and Muto, 2021).

A question arises here. Why can equilibrium response be prevented in principle? To find an answer to this fundamental conundrum, it may be useful to return to and examine the precise meanings of steadiness and unsteadiness of external forcing and stratigraphic configuration. With respect to external forcing, it has already been quantitatively defined in autostratigraphy that any external forcing at constant rates is considered to be steady, otherwise unsteady (Muto et al., 2016b). No such clear criterion has been provided as to whether the stratigraphic configuration is steady or unsteady, on the other hand. The main objectives of the present discussion are (1) to give a clear quantitative definition of steady stratigraphic configuration, (2) to examine when and how steady stratigraphic configuration can be realized, and (3) to clarify the intrinsic rarity of equilibrium response. We state that the discussion below focuses on the interactions of sediment supply and relative sea-level change (or base level, which incorporates eustatic sea level and tectonic activity). The effect of sediment redistribution by other processes such like waves, currents and tides are not considered.

2. The two parameters

A basin margin setting where an active fluvio-deltaic system is being fed by upstream terrestrial sediment is considered here. In this setting, the configuration of the shoreline trajectory in depositional dip section can serve as an appropriate proxy to define stratigraphic configurations (Helland-Hansen and Gjerberg, 1994; Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009). If the shoreline trajectory is straight or stationary, it can be regarded as a type of steady configuration, otherwise unsteady configuration. The stability of the stratigraphic configuration can thus be characterized by two parameters, the rate of shoreline progradation (R_{pro}) and the rate of topset aggradation (R_{agg}). These two parameters can represent most stratigraphic responses and the resulting configurations (e.g., $R_{agg} > 0$ for aggradation; $R_{agg} < 0$ for degradation; $R_{agg} = 0$ for alluvial grade; $R_{pro} > 0$ for progradation; $R_{pro} < 0$ for retrogradation; and $R_{pro} = 0$ for stationary shoreline).

3. Steady and unsteady stratigraphic configuration

In this section, we concern the stability of stratigraphic configuration. We declare that the discussion of these configurations is independent of external forcings (either steady or unsteady), though potential formation mechanisms are discussed.

3.1. The seven classes of steady stratigraphic configuration

Steady stratigraphic configuration corresponds only to a constant ratio of R_{agg}/R_{pro}, or one of these two rates remains zero during the time interval of interest. A total of 7 classes of steady stratigraphic configuration that satisfies such condition of R_{agg} and R_{pro} can be defined based on this criteria (Fig. 2), as follows.

(1) Steady accretionary retrogradation ($R_{agg} > 0$, $R_{pro} < 0$, R_{agg}/R_{pro} = constant < 0; Fig. 2a). The shoreline retreats landward and also migrates upward due to sediment accretion landward of the shoreline. This happens when the aggradation of the coastal plain keeps pace exactly with the relative sea-level rise. The rate of the relative sea-level rise can increase or decrease, which must be accompanied by the same magnitude of change in topset accretion. If upstream sediment supply is available, $R_{agg} \leq 0$ cannot occur with $R_{pro} < 0$. Such kind of configuration has been reported as autobreak or sediment-starved autoretreat (Muto, 2001; Parker et al., 2008).
(2) Steady aggradation with no retrogradation or progradation ($R_{agg} > 0$ and $R_{pro} = 0$; Fig. 2b). The shoreline never advances or retreats, but moves straightly upward. This happens when the rate of sedimentation at the shoreline is equal to the rate of the relative sea-level rise, so that the shoreline remains stationary through time. The result of this type of stratigraphic configuration can be exemplified by the conceptual model that produces an 'aggradational parasequence set' as proposed by sequence stratigraphy (Van Wagoner et al., 1988).
(3) Steady aggradation with progradation ($R_{agg} > 0$, $R_{pro} > 0$, R_{agg}/R_{pro} = constant > 0; Fig. 2c). Since both progradation and topset aggradation can occur regardless of whether relative sea-level is rising, falling, or stationary, three subclasses can be classified with respect to relative sea-level change (cases a-c in Fig. 2c). During relative sea-level rise, topset aggradation is inevitable, and progradation may occur, known as normal regression (Posamentier et al., 1992; Helland-Hansen and Gjerberg, 1994) or precursory regression (Muto and Steel, 1997) (case a in Fig. 2c). On the other hand, during relative sea-level fall, progradation is inevitable, and topset aggradation may occur (case c in Fig. 2c). High alluvial-plain gradients and/or low basin-floor gradients favor this kind of conditions (Posamentier et al. 1992; Helland-Hansen and Martinsen, 1996; Petter and Muto, 2008). At stationary relative sea-level, the shoreline trajectory always shows a horizontal line extending basinward (case b in Fig. 2c). In all of these subclasses, progradation must keep pace with topset aggradation.
(4) Alluvial grade with fixed downstream boundary ($R_{agg} = R_{pro} = 0$; Fig. 2d). Alluvial grade is the dynamic equilibrium state where neither aggradation nor degradation occurs despite substantial sediment transport (Mackin, 1948),

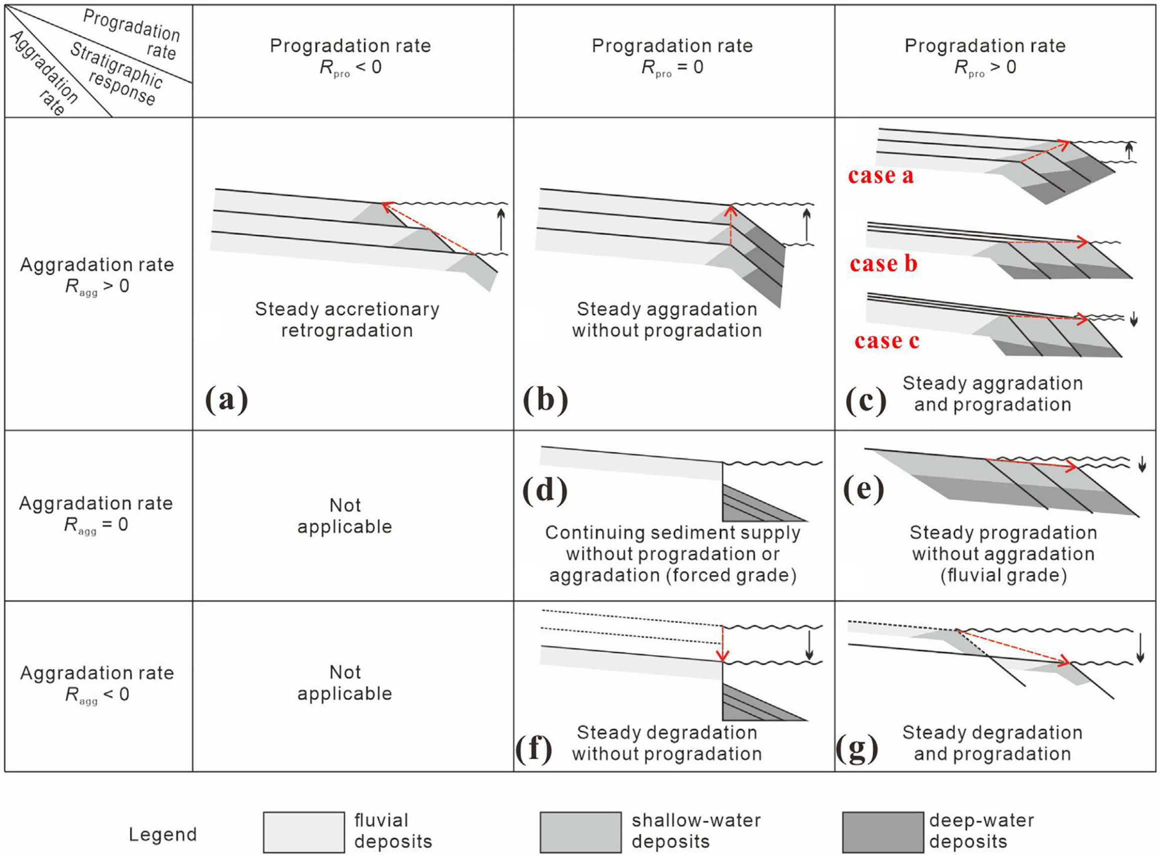

Fig. 2. Schematic illustration of the basic steady stratigraphic configurations. These steady configurations are defined with a constant ratio of aggradation rate to progradation rate (i.e., R_{agg}/R_{pro}), as reflected by straight shoreline trajectories (a-c, e-g) or stationary shoreline (d). The red dotted lines with arrow indicate shoreline trajectories. Note that these steady configurations are independent of external forcings. They may be formed under either steady or unsteady external forcing settings.

and can be a reasonable cause for a steady stratigraphic configuration. Alluvial grade can be forcibly attained with a stationary base level if the downstream end of the depositional system is fixed ($R_{pro} = 0$). This type of grade is referred to as forced grade by Muto et al. (2016a). Examples of forced alluvial grade include a non-deltaic alluvial river that is dammed up by a downstream weir (Parker and Anderson, 1977), and a deltaic alluvial river that has reached the 'shelf edge' where the feeder flows simply dump all the supplied sediment into very deep water (Kim et al., 2013; Muto et al., 2016a; Wang et al., 2019a). This can happen when the slope of the basinward downlap surface is steeper than that of the foreset surface.

(5) Alluvial grade with the moving downstream boundary ($R_{agg} = 0$ and $R_{pro} > 0$ while $R_{agg}/R_{pro} = 0$; Fig. 2e). Alluvial grade can also be attained in unfixed downstream boundary settings. The only case is the basinward extension of an existing graded river profile and thus $R_{pro} > 0$. In this case, relative sea-level fall is a necessary condition. Alluvial grade attained with relative sea-level fall has been demonstrated in both experiments and field data (Muto and Swenson, 2005, 2006; Wang et al., 2019b).

(6) Alluvial degradation with a fixed downstream boundary ($R_{agg} < 0$ and $R_{pro} = 0$; Fig. 2f). Alluvial degradation is another reasonable cause for a steady stratigraphic configuration. This is because only the youngest topset surface of the interval of interest is represented, as older surfaces have been eroded. Two types of degradation can be classified depending on the downstream boundary condition, i.e. degradation with fixed downstream boundary as discussed in case (4) and degradation with moving downstream boundary as discussed in cases (5) and the following (7). The former is of more theoretical importance, since it is difficult to find a natural example according to the present knowledge.

(7) Alluvial degradation with a moving downstream boundary ($R_{agg} < 0$ and $R_{pro} > 0$ while R_{agg}/R_{pro} = constant < 0; Fig. 2g). It is more practical to discuss a degradational system that also extends basinward. The shoreline trajectory left by forced regression as defined in sequence stratigraphy is equivalent to this type of configuration (Posamentier et al. 1992; Helland-Hansen and Martinsen, 1996). Numerous examples can be found in the literatures.

3.2. The three classes of unsteady stratigraphic configuration

If the shoreline trajectory in depositional dip section shows a curved patten, i.e. changing R_{agg}/R_{pro} ratio, the corresponding stratigraphic configuration is regarded as unsteady. For an accretionary growing system, a total of 3 classes and 6 subclasses of unsteady stratigraphic configuration can be defined (Fig. 3), as follows.

(1) Accretionary retrogradation with curved shoreline trajectory (Fig. 3a, b). According to the bending pattern of shoreline trajectory, two subclasses can be classified, i.e. upward convex and upward concave. The upward convex one means acceleration of retrogradation (decreasing R_{agg}/R_{pro}, Fig. 3a) which may result from acceleration of relative sea-level rise and/or decrease of sediment input. On the contrary, the upward concave one means deceleration of retrogradation (increasing R_{agg}/R_{pro}, Fig. 3b) which may result from deceleration of relative sea-level rise and/or increase of sediment input.

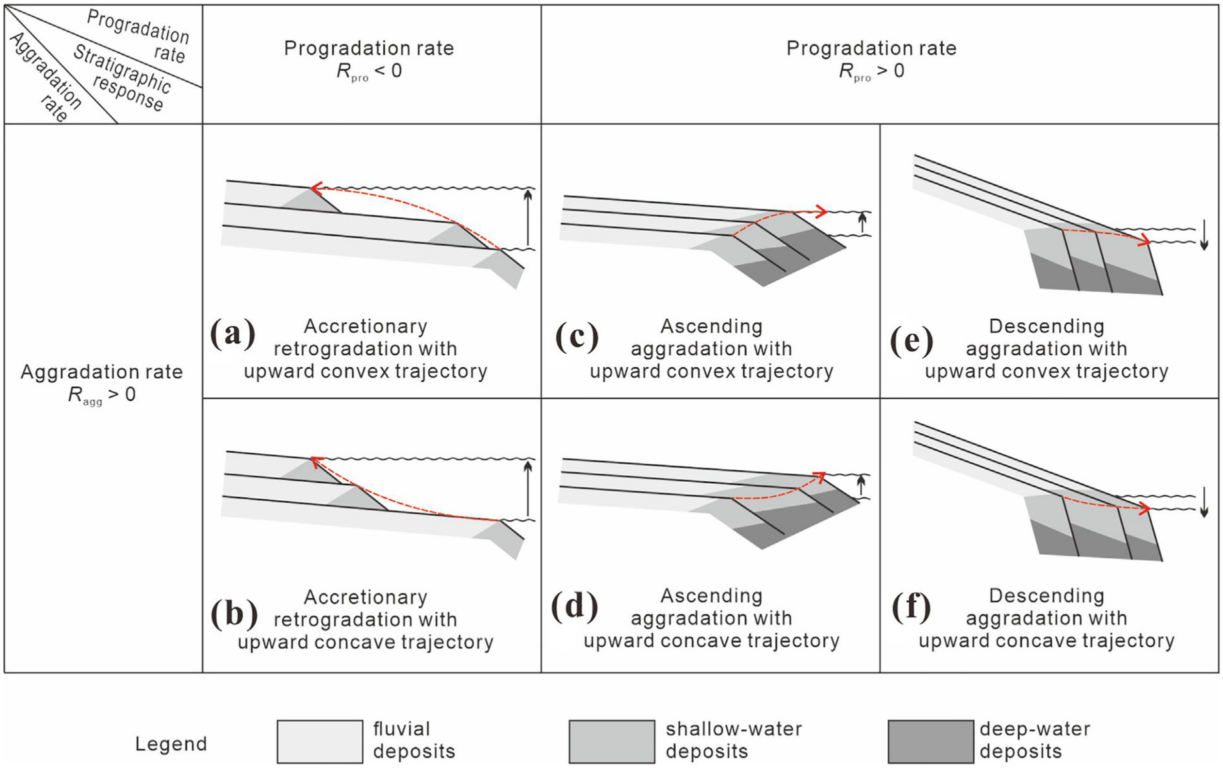

Fig. 3. Schematic illustration of the basic unsteady stratigraphic configurations. These unsteady configurations are defined with varying ratio of aggradation rate to progradation rate (i.e., R_{agg}/R_{pro}), as reflected by the curved shoreline trajectories. (a, b) Accretionary retrogradation with upward convex and concave trajectories, respectively. (c, d) Ascending progradation with upward convex and concave trajectories, respectively. (e, f) Descending aggradation with upward convex and concave trajectories, respectively. Note that these unsteady configurations are independent of external forcings. Some of them might be formed under either steady or unsteady external forcing settings. See the main text for elaboration.

(2) Progradation with aggradation in the context of relative sea-level rise (ascending progradation) which produces curved shoreline trajectory (Fig. 3c, d). It is common for normal regression or precursory regression to show such kind of trajectories, which may also be either convex upward (decreasing R_{agg}/R_{pro}, Fig. 3c) or concave upward (increasing R_{agg}/R_{pro}, Fig. 3d). Slowing down of relative sea-level rise and/or increase input of sediment would favor the former condition and the opposite for the later.

(3) Progradation with aggradation in the context of relative sea-level fall (descending aggradation) which produces curved shoreline trajectory (Fig. 3e, f). In the setting of relative sea-level fall where topset aggradation sustains as discussed above, a descending progradational shoreline trajectory would be preserved. The trajectory may also be either convex upward (increasing R_{agg}/R_{pro}, Fig. 3e) or concave upward (decreasing R_{agg}/R_{pro}, Fig. 3f), mostly relating to accelerating and decelerating of relative sea-level fall, respectively.

We declare that to form these unsteady stratigraphic configurations, changing external forcing might be an important cause but does not have to be the sufficient condition. It has been proven that some of these unsteady stratigraphic configurations can be formed under steady external forcings. For example, in the experiment of Muto (2001), the shoreline trajectory of a growing delta experiences a precursory advance and a subsequent retreat. During this process, the rates of relative sea-level rise and sediment supply were kept constant, i.e. steady external forcing, so the advance-to-retreat transition of shoreline movement was autogenic and this phenomenon was named as shoreline autoretreat (Fig. 4; Muto, 2001). During the shoreline advance phase, the shoreline trajectory showed an upward concave pattern like shown in Fig. 3d; and during the shoreline retreat phase, the shoreline trajectory showed an upward convex pattern like shown in Fig. 3a. In the experiment of Wang and Muto (2021), a transgressive shoreline trajectory concaving upward like the one shown in Fig. 3b was produced with steady relative sea-level rise and sediment supply, as discussed below.

4. Discussion: the rarity of equilibrium response and the universal of non-equilibrium response

Whether a response is equilibrium or non-equilibrium is determined by the correspondence between the stability of external forcing and that of the resultant stratigraphic configuration. A fundamental issue is that given steady (rate constant) external forcings, what kind of stratigraphic configuration would be formed. A clear understanding of this issue would favor stratigraphic interpretation in more common and complex settings (mostly characterized by unsteady external forcing).

As pointed in autostratigraphy, steady external forcing generally gives rise to unsteady stratigraphic configuration, i.e. the non-equilibrium is universal. To illustrate this, the first topic should be discussed is when and how equilibrium responses operate? Why they are rare? And what, if any, are the peculiarities of these equilibrium responses? Since the following discussion relies heavily on the history of the shoreline trajectory, which is further dependent on the accretionary process and the resulting stacking pattern of strata, cases related to degradation and thus unconformity (i.e., shoreline trajectory history is missing; Fig. 2f, g) are not considered.

External forcing is mainly exerted by sediment supply and the behavior of relative sea-level (Posamentier et al., 1988; Kim et al., 2006). Thus, steady external forcing means that the rate of rela-

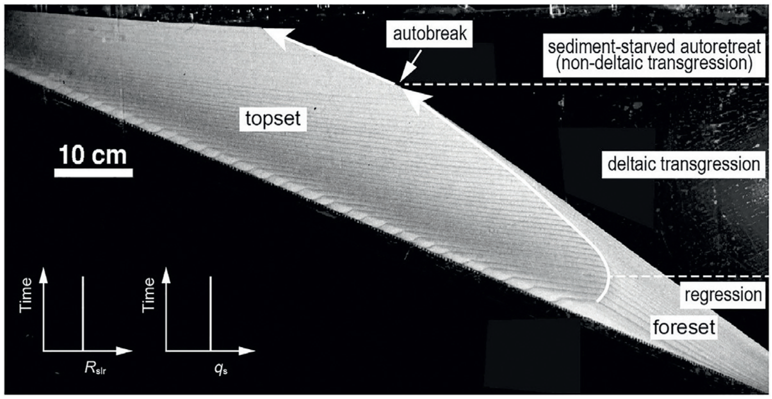

Fig. 4. Annotated image from the end of one of the experiments of Muto (2001) in which shoreline autoretreat was reported. With a constant rate of relative sea-level rise (R_{slr}) and a constant rate of sediment supply in unit width (q_s) (i.e., a steady external forcing), the shoreline initially advances seaward and then retreats landward (autoretreat), leaving a progradational concave upward trajectory and a retrogradational convex upward trajectory, respectively. This represents an unsteady stratigraphic configuration and thus a non-equilibrium response. In the late stage of autoretreat, the system loses its subaqueous part and the shoreline trajectory tends to be linear after an event called autobreak. In this post-autobreak stage, the equilibrium response is realized. For details of the experimental conditions, see Muto (2001).

tive sea-level change (R_{sl}) and the rate of upstream sediment supply (Q_s) are constant. It is worth noting that in the discipline of stratigraphy, it is not very meaningful to consider $Q_s \leq 0$ and thus no sediment accumulation and stratigraphic accretion. Thus, the steady external forcing discussed below involves Q_s = constant > 0, unless otherwise specified. By comparison, steady relative sea-level change means any constant value of R_{sl} ($R_{sl} > 0$ for rise; $R_{sl} < 0$ for fall; $R_{sl} = 0$ for relative sea-level standstill).

4.1. Equilibrium response with stationary relative sea-level

If the relative sea-level remains stationary ($R_{sl} = 0$), the extension of the river profile will always result in a horizontal shoreline trajectory (case b in Fig. 2c). There is also a case where a river pours into a basin with a very steep basinfloor so that the river cannot extend (Kim et al., 2013; Muto et al., 2016a; Wang et al., 2019a; Fig. 2d). In the latter case, the shoreline would remain stationary. Both steady stratigraphic configurations can be produced with a steady sediment supply, and are thus consistent with the definition of equilibrium response. It is worth noting that the steady stratigraphic configuration in these two cases is entirely determined by the static relative sea-level and basin configuration, i.e., it does not matter whether the rate of sediment supply is constant or not.

4.2. The rarity of equilibrium response with steadily rising relative sea-level

Things are much more complicated when the relative sea-level is rising or falling. In such settings, the shoreline moves, and so do the upstream and downstream boundaries of the alluvial realm, where the upstream boundary is the alluvial-basement transition (ABT) and the downstream boundary is the delta toe or the downlapping point. As a result, the area of the depositional surface would be variable which depends on the basin configuration and relative sea-level change. If we consider a steady external forcing and thus a steady sediment supply (Q_s = constant > 0), the depositional rate at the shoreline tends to be variable. The combined function of unsteady shoreline aggradation and steady relative sea-level rise would yield nonlinear shoreline trajectories and thus unsteady stratigraphic configurations. Thus, non-equilibrium response prevails under conditions of changing relative sea-level. Only under some special circumstances can equilibrium response be attained.

The steady accretionary retrogradation shown in Fig. 2a is generally accompanied by a shrinking of the alluvial surface. Since the surface area tends to decrease during this process, the rate of aggradation tends to increase in response, assuming a steady sediment supply. As a result, the shoreline trajectory (transgressive surface) tends to steepen landward, resulting in a concave upward profile (Figs. 3b, 5; Wang and Muto, 2021). Maintaining a linear transgressive shoreline trajectory requires either a reduction in sediment supply or a slowing down of relative sea-level rise, or a combination of both.

There is a special case where the steady accretionary retrogradation shown in Fig. 2a can be maintained by equilibrium response. Under the condition that the slope of the hinterland where the alluvial system onlaps is gentler than that of the pre-existing subaqueous foreset, the alluvial realm can be reduced to a critical length (in 2D consideration) or area (in 3D consideration) and maintained thereafter. This has been exemplified by the sediment-starved shoreline autoretreat that occurs after a critical stratigraphic event known as autobreak (Muto, 2001; Parker et al., 2008; Wu et al., 2020; Fig. 4), and the rate-constant transgression after the rate of transgression has been reduced to a minimum that occurs in over-extended alluvial systems (Wang and Muto, 2021; Fig. 5).

The steady aggradation without progradation or retrogradation, shown in Fig. 2b, requires the rate of shoreline aggradation to be equal to the rate of relative sea-level rise. This condition can rarely be attained with steady forcing by constant rates of relative sea-level rise and sediment supply, because the rate of aggradation is inevitably reduced by expansion of the alluvial surface (including both subaerial and subaqueous realms). In other words, to maintain this pure aggradational phase, the sediment supply rate must increase to prevent the shoreline aggradation rate from decreasing; and/or the rate of relative sea-level rise must decrease to keep pace with the reduced aggradation rate. The conventional view of sequence stratigraphy, which interprets Fig. 2B as a balanced state of sediment supply and relative sea-level rise and implies an equilibrium response (Van Wagoner et al., 1988; Shanley and McCabe, 1994), considers only a small part of the depositional system (i.e., the shoreline and its vicinity) and ignores what happens at the proximal and distal ends of the alluvial-deltaic system.

Similar explanations can be extended to cases a and c in Fig. 2c. In these cases (Fig. 2b, c), both topset and foreset evolve with relative sea-level change. Under steady external forcing, it is difficult to maintain a constant R_{agg}/R_{pro} value and thus a steady stratigraphic configuration. This is the rationale that non-equilibrium responses are more prevalent.

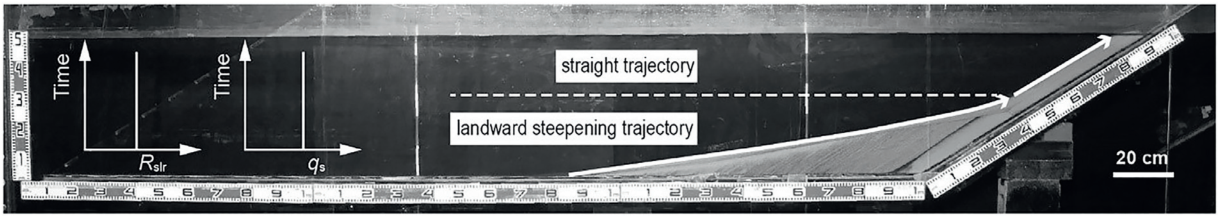

Fig. 5. Annotated image from Wang and Muto's (2021) experiments in which non-deltaic transgression occurred immediately as relative sea-level rose in front of over-extended alluvial-deltaic systems. With a constant rate of relative sea-level rise (R_{slr}) and a constant rate of sediment supply in unit width (q_s) (i.e., a steady external forcing), the shoreline trajectory steepens landward (non-equilibrium response). In the late stage, the shoreline trajectory tends to be linear, where the equilibrium response is realized. For details of the experimental conditions, see Wang and Muto (2021).

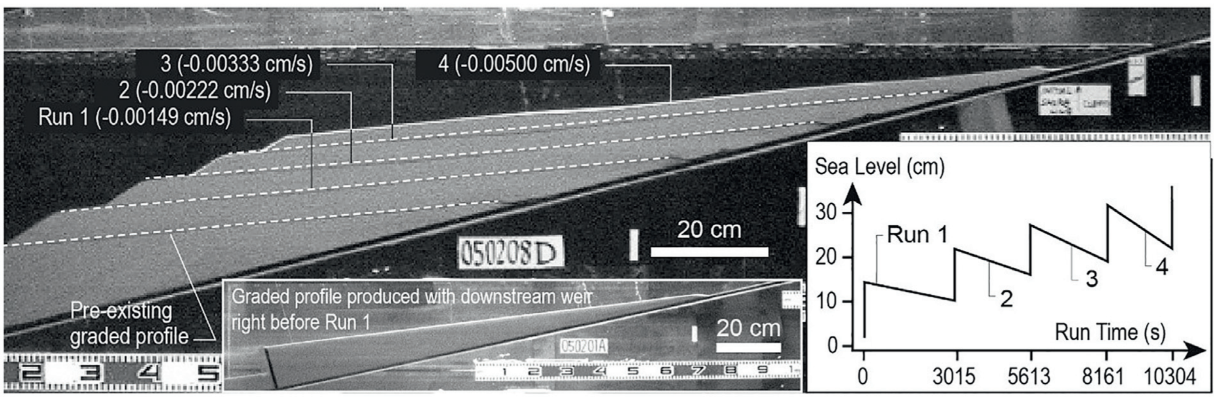

Fig. 6. Autogenic grade river profiles produced in a series of 2D flume experiments (from Muto, 2011). Parallel river profiles in 4 experiments reflect the state in which the grade was attained (i.e., steady stratigraphic configuration). The rate of relative sea-level fall was constant during each run, but increased from Run 1 to Run 4 (see the inset diagram). Upstream water and sediment discharges were held constant throughout the entire series (i.e., steady external forcing). Each run began after a rapid increase in relative sea-level rise at the end of the previous run. The foreset prograded over the inundated graded river profile so that the slope of the basinfloor was equal to that of the graded river bed. Equilibrium response was realized in each of the 4 relative sea-level drops. For details of the experimental conditions, see Muto and Swenson (2006).

4.3. The rarity of equilibrium response with steadily falling relative sea-level

In the steady progradation without topset aggradation shown in Fig. 2e, the alluvial river reaches a graded state with falling relative sea-level. All the sediment supplied from upstream is consumed for foreset progradation. Whether the graded state can be maintained with a steady falling of relative sea-level and sediment supply (equilibrium response) depends largely on the slope of the basinfloor (downlap surface). The equilibrium response can only be attained in the condition where the slope of the basinfloor is equal to that of the graded riverbed. In this case, with a steady falling of relative sea-level, the alluvial-deltaic system will adjust itself to reach a critical set thickness so that the water depth in front of the delta just accommodates all the sediment supplied from upstream. This has been exemplified by a flume experiment that produced an autogenic alluvial grade (Muto and Swenson, 2006; Fig. 6).

Except for this peculiar condition, equilibrium response with relative sea-level fall can hardly be attained. For example, if the slope of the basinfloor is steeper than that of the graded river bed, continuous progradation with relative sea-level fall will gradually form a higher foreset slope as the water depth in front of the delta becomes deeper. This means that the amount of sediment required for progradation is continuously increasing. Thus, the maintenance of alluvial grade requires a slowing of relative sea-level fall and/or an increase in sediment supply, so that the case shown in Fig. 2E can only be realized by non-equilibrium response if the slope of the basinfloor is steeper than that of the river bed. This has been exemplified by flume experiment, where alluvial grade (steady configuration) was maintained by slowing the relative sea-level fall of a particular pattern while keeping sediment supply constant (Muto and Swenson, 2005).

Conversely, if the slope of the basinfloor is gentler than that of the graded riverbed, continuous progradation with relative sea-level fall will form a lower foreset slope as the water depth in front of the delta becomes shallower. Maintaining alluvial grade requires accelerating relative sea-level fall and/or decreasing sediment supply. Otherwise, the alluvial-deltaic system will evolve into a sustained aggradational stage (Petter and Muto, 2008). It is worth mentioning that even if the alluvial river reaches the state of grade, it cannot be sustained because the water depth in front of the alluvial river would eventually approach zero, and then the shoreline detaches from the alluvial system (Petter and Muto, 2008), and the alluvial-deltaic system evolves into a (non-deltaic) alluvial system with net aggradation.

5. Conclusions

One manifestation of steady stratigraphic configuration is the shoreline trajectory being straight or the shoreline being stationary during the interval of interest. The behavior of aggradation and progradation can be used as proxies to demonstrate this peculiarity. A constant ratio between the rate of aggradation and the rate of progradation, or one of these two rates being zero, will produce steady stratigraphic configurations. Otherwise, if the shoreline trajectory exhibits a curvature, for example, the stratigraphic configuration is considered as unsteady.

When a steady stratigraphic configuration is formed with steady external forcing, the equilibrium response is considered, where steady external forcing means that both the rate of relative sea-level change and the rate of upstream sediment supply are constant. For a growing alluvial-deltaic system, it is common that its surface area either expands or shrinks, but rarely remains constant, although special cases exist. Thus, the rate of shoreline aggradation is commonly unsteady (changing rate), given a constant rate of sediment supply. The unsteady shoreline aggradation versus steady relative sea-level change results in nonlinear shoreline trajectories. Thus, non-equilibrium responses prevail during stratigraphic processes.

Equilibrium responses are physically possible under three special circumstances, according to the current knowledge:

(1) Synchronous aggradation and progradation with standstill relative sea-level, or null aggradation and progradation with standstill relative sea-level due to sudden termination of the alluvial river (e.g., rivers ending in extremely deep basin margins).
(2) With steady relative sea-level rise and sediment supply, the alluvial system may eventually retrograde with constant length, so that a steady stratigraphic configuration is formed. This happens under the condition that the slope of the hinterland where the alluvial system onlaps is gentler than that of the preexisting subaqueous foreset, and the alluvial system loses its subaqueous foreset part but evolves as a pure, or non-deltaic, alluvial system with unchanged longitudinal length or surface area (only the topset aggrades).
(3) With steady relative sea-level fall and sediment supply, the alluvial river can attain and maintain the graded state, which represents a type of steady stratigraphic configuration. This happens under the condition that the slope of the basinfloor, where the foreset downlaps, is equal to that of the overlying graded alluvial river. The system evolves as a pure prograding system (only the foreset develops with no topset aggradation).

One of the basic notions underpinning the conventional sequence stratigraphy is that strata are stacked by equilibrium response to steady external forcing; a corollary of this is that the change in strata stacking pattern indicates a change in external forcing. The problem with the conventional sequence stratigraphy is that it considers only a small part of the depositional system (i.e., the shoreline and its vicinity) and overlooks the effect of the size of the whole system, which generally changes as the system evolves.

Declaration of competing Interest

The authors have no conflict of interest to declare.

CRediT authorship contribution statement

Junhui Wang: Conceptualization, Formal analysis, Software, Visualization, Writing – original draft. **Tetsuji Muto:** Conceptualization, Formal analysis, Visualization, Validation, Writing – review & editing.

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