Construction and destruction of an autogenic grade system: The late Holocene Mekong River delta

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ABSTRACT

Grade, a fundamental concept in river geology and geomorphology, refers to a long-term sediment balance that is accompanied by zero net deposition and erosion. Recent physical and theoretical modeling proposed the notion that downstream alluvial rivers can autogenically attain grade only in a particular set of environmental conditions that include a constant fall of relative sea level. We here make the first successful identification of an autogenic grade system in the geological record: the late Holocene Mekong River delta. From 3.5 ka to subrecent, the delta exhibits peculiar features, including (1) no trace of significant sediment accumulation and erosion on the delta plain surface, (2) a delta plain surface with the same slope as the underlying shelf surface, (3) distributary channels that are stabilized in transverse directions but extend linearly basinward, and (4) a delta set thickness that matches a theoretical value. These features in combination are indicative of autogenic grade. Coastal dispersal of river-derived sediment by tides,

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waves, and ocean currents, as well as tectonic features and mangrove vegetation, may have contributed to the attainment and maintenance of grade. Ongoing drastic changes in sea level and human activities have caused the downstream Mekong River to become ungraded and unstable with a much higher risk of channel avulsion and shifting than in the past.

INTRODUCTION

Grade refers to the state of a river where sediment is conveyed without net deposition or net erosion (Gilbert, 1877; Mackin, 1948). A correct understanding of alluvial grade is fundamental to the geology and geomorphology of rivers and related environments (Posamentier and Vail, 1988; Muto et al., 2007; Pittaluga et al., 2014) because it represents the critical boundary condition between river aggradation and degradation and because grade is a key to the exploration of fluvial response to base-level forcing and the prediction of long-term river behaviors. Nevertheless, there has been no documented identification of a graded alluvial river from stratigraphic records, largely because 1) by definition graded rivers leave neither depositional nor erosional features on the riverbeds; and 2) the prevailing notion in sequence stratigraphy is that alluvial grade is attained during sea level stillstand (Posamentier and Vail, 1988). This prevailing notion has recently been proven misleading, i.e., it is valid only for downstream-fixed settings where the delta fed by the river is unable to prograde basinward (Muto et al., 2016).

The autostratigraphy theory of grade has resulted in a realization that for more common settings where the delta can prograde the attainment of grade requires a falling relative sea level (Muto et al., 2016). Based on this updated notion, here we make the first report of a natural autogenic grade system from stratigraphic records. As demonstrated below, the 3.5 ka to subrecent Mekong River delta satisfies an array of theoretical criteria for identifying autogenic grade (Table 1; Muto and Swenson, 2006).

AUTOGENIC GRADE AND HOW IT IS RECORDED IN STRATA

Table 1 outlines the prerequisites for autogenic alluvial grade: a constant relative sea level fall (rate R_{sl} = const < 0; R_{sl} > 0 for rise), a constant supply of sediment (rate Q_s = const), and an alluvial slope (α) that equals the slope of the shelf surface (ϕ) (Muto and Swenson, 2006). A delta fed by an autogenic graded alluvial river is characterized by 1) distributary channels that are least subject to avulsion and lateral shifting but extend basinward in a linear trend (Muto et al., 2016), and 2) a set thickness ($h_{\mathrm{set\_theory}}$) given by:

$$h_{\mathrm{set\_theory}} = \frac{\Lambda_{\mathrm{3D}}}{\sqrt{1+\alpha^{-2}}}, (1)$$

$$\Lambda_{\mathrm{3D}} = \sqrt{\frac{Q_s}{|R_{\mathrm{sl}}|}}, (2)$$

where Λ_{3D} is autostratigraphic length scale considered in three dimensions (Muto et al., 2016). An $h_{\mathrm{set\_theory}}$ value can be realized either by aggradation if the actual delta set thickness (h_{set}) is thinner than $h_{\mathrm{set\_theory}}$, or by degradation in the opposite case. The closeness of h_{set} to $h_{\mathrm{set\_theory}}$ indicates that the topset alluvial system is close to grade.

The realization of $\phi \sim \alpha$ is likely only if the alluvial system has extended far basinward before the onset of relative sea level rise. Any downstream alluvial system facing relative sea level rise has critical values of alluvial length (L_{crt}) and delta plain area (A_{crt}), beyond which it cannot sustain deltaic sedimentation (Tomer et al., 2011). L_{crt} and A_{crt} are approximately equal to Λ_{3D} and Λ_{3D}^2, respectively:

$$L_{\mathrm{crt}} \sim \Lambda_{\mathrm{3D}}, (3)$$

$$A_{\mathrm{crt}} \sim \Lambda_{\mathrm{3D}}^2, (4)$$

Suppose that the feeder river has attained an alluvial length (L) and/or a delta plain area (A) far beyond the critical values that are expected given a rise of sea level. In this case, the alluvial system undergoes nondeltaic rapid transgression, leaving a sediment-starved flooding surface, the distal part of which can be a relict of the drowned delta plain that then becomes part of the outer shelf surface.

THE HOLOCENE MEKONG RIVER DELTA AND DATABASE

The Holocene Mekong River delta (Fig. 1) has experienced four distinct stages: 1) 8.4−6.3 ka when deltaic sedimentation was initiated by decelerating postglacial sea-level rise; 2) 6.3−3.5 ka when the delta prograded under the influence of tides during the sea level highstand; 3) 3.5 ka to subrecent when further deltaic progradation occurred under the influence of mixed tide- and wave-processes due to relative sea level fall; and 4) the past several decades during which deltaic sedimentation has declined largely due to anthropogenic environmental changes (Ta et al., 2005; Anthony et al., 2015). The third and fourth stages are examined below.

Database of the 3.5 ka−subrecent Mekong River Delta System

During the third stage, distributary channels extended over 100 km in a linear basinward trend (Fig. 1) without building distinct natural levees (Gugliotta et al., 2017). In spite of this, the channels seldom avulsed or shifted laterally, as indicated by well-preserved 3.5 ka−subrecent beach ridges in interdistributary regions (Fig. 2; Tamura et al., 2012). These features make the Mekong River delta peculiar compared with other major existing deltas, most of which have grown by frequent channel avulsions (e.g., the Yellow River delta; ref. Saito et al., 2000).

Figure 3 shows a time-calibrated section (X−X' in Fig. 1) which is based partly on chronological data from 5 drilling columns (PSG, DT1, VL1, TC1 and TV1) and from beach ridge relicts. The preservation of seaward-younging beach ridges indicates that since 3.5 ka the Mekong River delta has been lacking clear features of alluvial sediment accumulation and erosion on the topset surface (the delta plain) but has been prograding monotonically onto a hiatal Vietnam Shelf surface (Fig. 3). The slope of the shelf ($\phi \sim 1 \times 10^{-4}$, from TC1 to VL1; ref. Fig. 3) is close to the current delta plain slope ($\alpha \sim 0.8 \times 10^{-4}$; measured by Google Earth and calibrated with Fig. 3). These two slopes give the deltaic clinoform a parallelogramic shape in longitudinal profile, with a uniform h_{set} of approximately 20−25 m (Fig. 3).

Estimates of R_{sl} and Q_s were compiled from references. During the past 3.5 ky relative sea level fell approximately 3 m at a rate of $R_{sl} = -9.0\times10^{-4}$ m/yr (Ta et al., 2002). The coeval Q_s data provided by Milliman and Meade (1983), Ta et al. (2002) and Liu et al. (2017) are in a stable range of $1.0-1.2\times10^{8}$ m^3/yr, if a sediment grain density of 2640 kg/m^3 and a porosity of 40% are assumed. With these Q_s and R_{sl} values, Λ_{3D} for the 3.5 ka−subrecent Mekong River delta is calculated to be 330−410 km. Using $\alpha \sim 0.8\times10^{-4}$, h_{set_theory} at autogenic grade (eq. 1) would thus be 26−33 m, which is 1.04−1.65 times as thick as the measured h_{set} values.

Database of the Anthropogenic Mekong River Delta System

In the fourth stage, the relative sea level has risen ($R_{sl} \sim 0.66–2.4\times10^{-2}$ m/yr), reflecting ongoing global sea level rise (rate: 0.3×10^{-2} m/yr) and local land subsidence (rate: $0.36–2.1\times10^{-2}$ m/yr) (Minderhoud et al., 2017). Moreover, due to human activities including dam construction and sand mining (Anthony et al., 2015), the sediment discharge of the downstream Mekong River has significantly decreased ($Q_s \sim 3.2\times10^{7}$ m^3/yr; Lu et al., 2014). With these recent changes in R_{sl} and Q_s, Λ_{3D} has decreased to ~40−70 km. Meanwhile, the channels have exhibited a decrease in stability, as evidenced by sediment accumulation in flood plains indicating avulsions (see locations between cores PSG and VL1 in Fig. 3) (Tamura et al., 2009).

DISCUSSION

Autogenic Grade of the 3.5 ka−subrecent Mekong River System

The 3.5 ka−subrecent Mekong River delta satisfies the conditions (1) $\phi \sim \alpha$, (2) $R_{sl} \sim$ const < 0, and (3) $Q_s \sim$ const, all of which are mandatory to the attainment of autogenic grade (Table 1). The primary evidence is visible in the longitudinal profile of the delta, which lacks clear traces of alluvial aggradation and/or erosion on the delta plain (Fig. 3). The stabilization and basinward linear extension of the distributary channels (Fig. 1), accompanied by no significant events of flooding, avulsion and lateral shifting (Fig. 2), support the interpretation of autogenic grade, which is also favored by an approximate agreement between measured h_{set} values and the h_{set_theory} value. This agreement was attained approximately 3.5 ka, prior to which the Mekong River delta had progressively declined in topset aggradation since 8 ka (Ta et al., 2002, 2005; Tamura et al., 2012; see Fig. 3). For comparison, a contemporary delta on the Vietnam shelf coast, the late Holocene Song Hong delta, was subject to substantially the same fall of relative sea level but evolved as an aggradational system associated with avulsions, mainly because of a drastic increase in Q_s during the last 2 ky (Tanabe et al., 2006).

Over-Extension of the Paleo-Mekong River and Realization of $\phi \sim \alpha$

The slope condition $\phi \sim \alpha$ can be attributed to an overextension of the paleo-Mekong River prior to the postglacial transgression. To apply equations 3 and 4 to the paleo-Mekong River system during the postglacial sea level rise, we tentatively assume that Q_s was not significantly different from the one for the previous 3.5 ky. During 21−8 ka, relative sea level rose approximately 110 m (Hanebuth et al., 2000) at an average R_{sl} value of 8.5×10^{-3} m/yr. With these values, L_{crt} and A_{crt} are calculated as 114−119 km and $1.3{-}1.4 \times 10^4$ km^2, respectively. On the other hand, the values of L and A for the paleo-Mekong River delta prior to the postglacial sea level rise are estimated as 340−520 km and 1.0×10^5 km^2, respectively; i.e., $L >> L_{crt}$ and $A >> A_{crt}$, on the assumption that the delta apex was at Phnom Penh in the Cambodian lowlands and the paleo-shoreline extended to the present shelf-edge position (Tjallingii et al., 2010; Fig. 1). This overextension then gave rise to rapid nondeltaic drowning of the abandoned delta plain and the development of a basically nondepositional Vietnam shelf with a slope close to α.

The rapid nondeltaic drowning possibly continued until the shoreline recessed landward to somewhere between cores DT1 and VL1 (Fig. 3), as is also illustrated by Fig. 1, in which the downstream boundary of a speculated delta plain (A_{crt} = 1.3−1.4×10^4 km^2) was close to the position of core DT1. The estimated downstream boundary is generally landward as compared to that shown in Fig. 3. This is because the core DT1 is located inside the paleo valley, in which much more river sediment was accumulated than outside the valley (Tjallingii et al., 2010). So the rapid shoreline recession was stopped at a more seaward position along the valley than estimated. The valley-filling process also contributed to smooth the flooding surface and favor the realization of $\phi \sim \alpha$.

Other Processes Affect Grade

The argument above takes only river processes into account. In fact, the Holocene Mekong River delta has developed under the influence of coastal processes (Ta et al., 2005). The longshore drifts caused by waves and ocean currents of the northeasterly winter monsoon dispersed 30−67% of the upstream-supplied sediment to the southwestward (Nittrouer et al., 2017). Moreover, tidal processes also disperse river-derived sediments across the shelf, forming subaqueous platforms (Fig. 2). These particular effects have forced the delta to evolve more transversely than in a fluvial-dominated autogenic grade system, the channel-lobes of which would have protruded basinward (Figure DR1 in the GSA Data Repository). Coastal processes might also account for a measured h_{set} value slightly smaller than the h_{set_theory} value, as they would have reduced the effectiveness of Q_s by dispersing some amount of sediment away from the deltaic system. In addition, tidal processes must have functioned to stabilize and/or straighten the distributary channels (Rossi et al., 2016).

Besides, a linearly-orientated fault system (Nguyen et al., 2000) is inferred to run along the south bank of the Bassac River (the most southern branch; Fig, 2). The fault might favor the straight configuration of the Bassac River by suppressing it from migrating to the south. In addition, the densely vegetated mangrove forests, widespread on the delta, might also have functioned to stabilize the substrate by their extensive root systems (Nguyen et al., 2000).

On the other hand, the backwater effect might have exercised an opposite influence, since it functions to decelerate downstream channel flow, enhance channel bed aggradation (Parker et al., 2008; Lamb et al., 2012), and thus suppress the realization of grade. The formation of mid-channel bars in Fig. 2B can be partly attributed to the backwater effect, and their progressive growth might have promoted the development of channel bifurcations (Tamura et al., 2012) even during the autogenic grade stage.

Termination of the Autogenic Grade Stage

The Anthropocene sea level rise has inevitably broken up the autogenic grade. Adopting the Λ_{3D} value of the recent Mekong River delta, L_{crt} and A_{crt} are estimated as 40−70 km and 0.16−0.49×10^4 km^2, respectively, much smaller than the scale of the present delta plain (L > 270 km, A > 3.5×10^4 km^2). Due to this, the downstream Mekong River system is subject to rapid landward retreat and has a much higher risk of channel avulsion and shifting with increased instability compared to the past 3.5 ky. Moreover, the backwater should be more effective due to sea level rise. Additionally, human activities such as sand mining have caused deepening of the river bed, which may enhance bank erosion and thus bank instability (Brunier et al., 2014). Combining these ongoing natural and anthropogenic changes, the Mekong River delta is prone to development of an ungraded, destructive stage.

THE INTRINSIC REALIZATION OF AUTOGENIC GRADE

The detection of autogenic grade from the late Holocene strata implies that graded alluvial systems are much more probable and detectable in stratigraphic records than ever expected.

Autogenic grade is *inevitably* realized only if a particular kind of dynamic external forcing remains constant for some time interval (e.g., 10^3 years), along with a particular basin slope setting that can also be realized autogenically during sea level cycles. A key notion here is that (1) nondeltaic rapid transgression across an overextended alluvial system can develop a shelf surface having the same or very close gradient to the alluvial slope ($\phi \sim \alpha$), and (2) during the subsequent sea level fall, the downstream alluvial system can approach and attain autogenic grade given R_{sl} ~ const (< 0) and Q_s ~ const. In the work of detecting autogenic grade systems from stratigraphic records, Λ_{3D} functions as an intrinsic parameter for the long-term behavior (e.g., aggradation, degradation, grade for $R_{sl} < 0$; extent of nondeltaic transgression for $R_{sl} > 0$) of alluvial-deltaic shelf systems growing in interaction with relative sea level cycles.

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FIGURE CAPTIONS

Figure 1. Terrain model of the Mekong River delta region, showing the positions of Holocene shorelines. Black broken lines indicate shorelines during the transgression (12 ka, 10 ka, 9.5 ka, 8.5 ka) (Tjallingii et al., 2010), and red broken lines indicate shorelines during the regression (4.5 ka, 4−3 ka, 3−2 ka) (Nguyen et al., 2000). X−X' is a longitudinal section crossing the drill cores shown in Figure 3. The green shaded square represents a speculated delta plain with an area of A_{crt} estimated using the available data for the 21−8 ka transgression. Terrain and bathymetric data are from British Oceanographic Data Centre (https://www.bodc.ac.uk/).

Figure 2. Time-elapsing azimuth diagram showing the stabilized positions of the five main channels (dashed lines) during the late Holocene (A), as constrained by the well-preserved beach ridges (B) (after Tamura et al., 2012). Azimuths measured from Phnom Penh, where the delta apex is assumed to have been located (Figure DR2 in the GSA Data Repository). There is a delta-front platform extending from the shoreline to the 4-m-deep isobath, offshore of which is the delta-front slope.

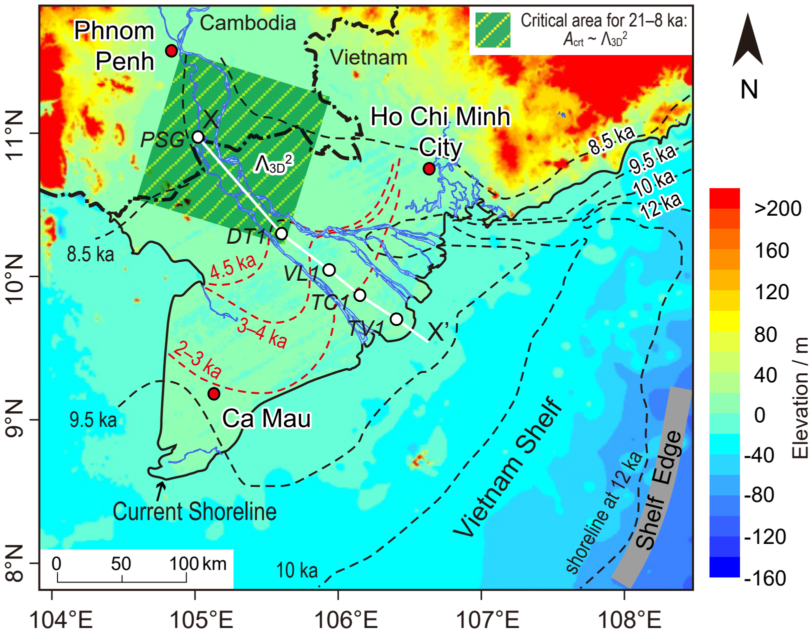
Figure 3. Cross section along the shoreline-perpendicular transect (X−X' in Fig. 1). Isochronous lines of 1.0 ka, 2.3 ka, 3.5 ka, 4.0 ka, 5.0 ka, and 8.0 ka were defined according to optically stimulated luminescence (OSL) ages of beach ridges and radiocarbon ages of drilling cores. The preservation and exposure of beach ridges indicate that the delta plain has been free from significant aggradation and degradation since 3.5 ka, which can reflect a graded state. Nondeltaic transgression is judged by the sedimentary hiatus between the Holocene and Pleistocene deposits, as calibrated by the radiocarbon ages of drilling cores. OSL ages are from Tamura et al. (2012). Core PSG is from Tamura et al. (2009); Cores DT1, VL1, TC1 and TV1 are from Ta et al. (2002, 2005) and Tanabe et al. (2003). OSL and radiocarbon ages are expressed relative to A.D. 2010.

TABLE CAPTIONS

Table 1. Criteria for identifying autogenic graded alluvial rivers.

[1]GSA Data Repository item xxx, Figure DR1 for sequential photographic images of an experimental delta approaching to grade autogenically; Figure DR2 for azimuth positions of the beach ridges, are available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1



Phnom Penh
Cambodia
Vietnam
Critical area for 21–8 ka: $A_{crt} \sim \Lambda_{3D}^2$
N
Ho Chi Minh City
PSG
X
Λ_{3D}^2
DT1
VL1
TC1
TV1
X'
8.5 ka
9.5 ka
10 ka
12 ka
4.5 ka
3–4 ka
2–3 ka
Ca Mau
Current Shoreline
Vietnam Shelf
shoreline at 12 ka
Shelf Edge
0
50
100 km
104°E
105°E
106°E
107°E
108°E
8°N
9°N
10°N
11°N
>200
160
120
80
40
0
-40
-80
-120
-160
Elevation / m

Figure 2

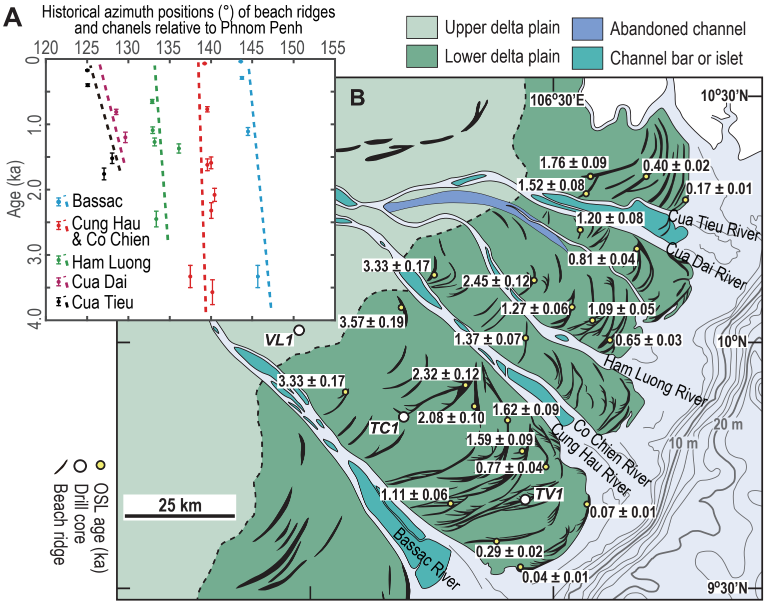
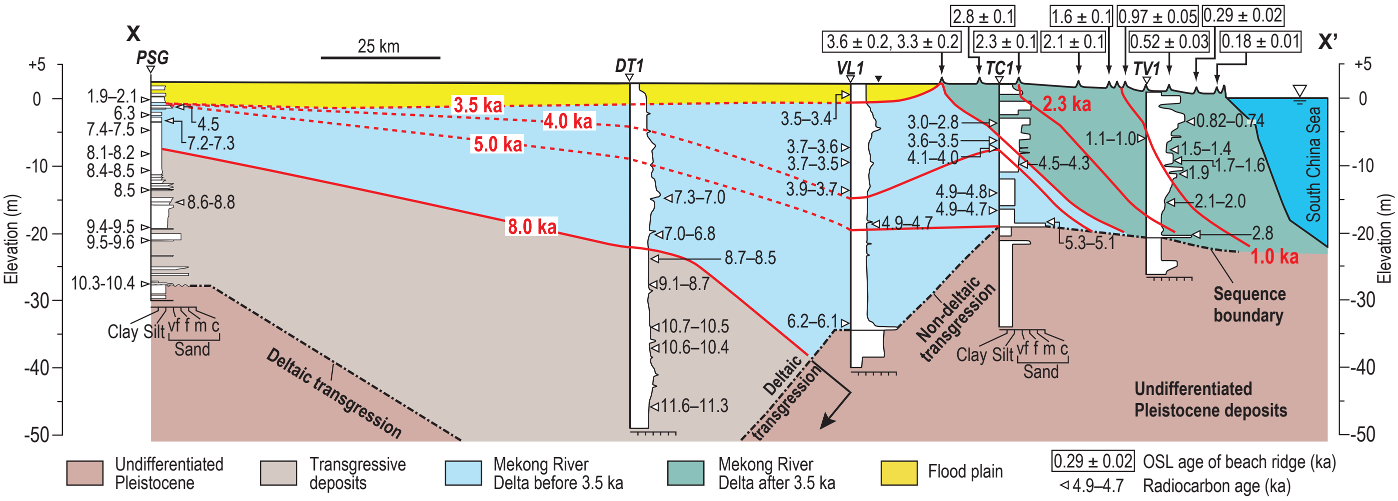

A
Historical azimuth positions (°) of beach ridges and chanels relative to Phnom Penh
120 125 130 135 140 145 150 155
Age (ka)
0 1.0 2.0 3.0 4.0
Bassac
Cung Hau & Co Chien
Ham Luong
Cua Dai
Cua Tieu
Upper delta plain
Lower delta plain
Abandoned channel
Channel bar or islet
B
106°30'E
10°30'N
10°N
9°30'N
1.76 ± 0.09
0.40 ± 0.02
1.52 ± 0.08
0.17 ± 0.01
1.20 ± 0.08
Cua Tieu River
Cua Dai River
0.81 ± 0.04
3.33 ± 0.17
2.45 ± 0.12
1.27 ± 0.06
1.09 ± 0.05
3.57 ± 0.19
1.37 ± 0.07
0.65 ± 0.03
VL1
Ham Luong River
3.33 ± 0.17
2.32 ± 0.12
TC1
2.08 ± 0.10
1.62 ± 0.09
1.59 ± 0.09
Co Chien River
Cung Hau River
0.77 ± 0.04
20 m
10 m
1.11 ± 0.06
TV1
0.07 ± 0.01
0.29 ± 0.02
0.04 ± 0.01
Bassac River
25 km
OSL age (ka)
Drill core
Beach ridge

Figure 3



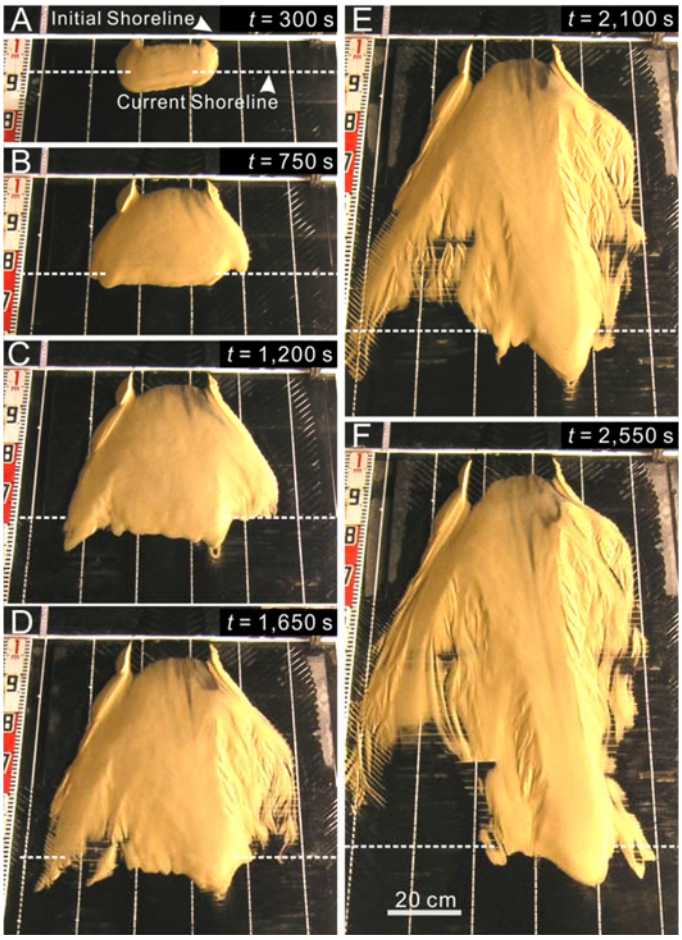


Figure DR1. Sequential photographic images of an experimental delta which was autogenically approaching to a graded state. The delta was built onto slope conditions that $\phi \sim \alpha \sim 0.07$, forced by constant $R_{sl} = -1.24 \times 10^{-3}$ cm/s and constant $Q_s = 0.293$ cm^3/s. The delta lobe was extending linearly basinward within the experimental time period from $t = 300-2550$ s. The distributary channels were less subject to lateral shifting and avulsion. Experiments referred to Muto et al. (2016), but different photos are presented here.

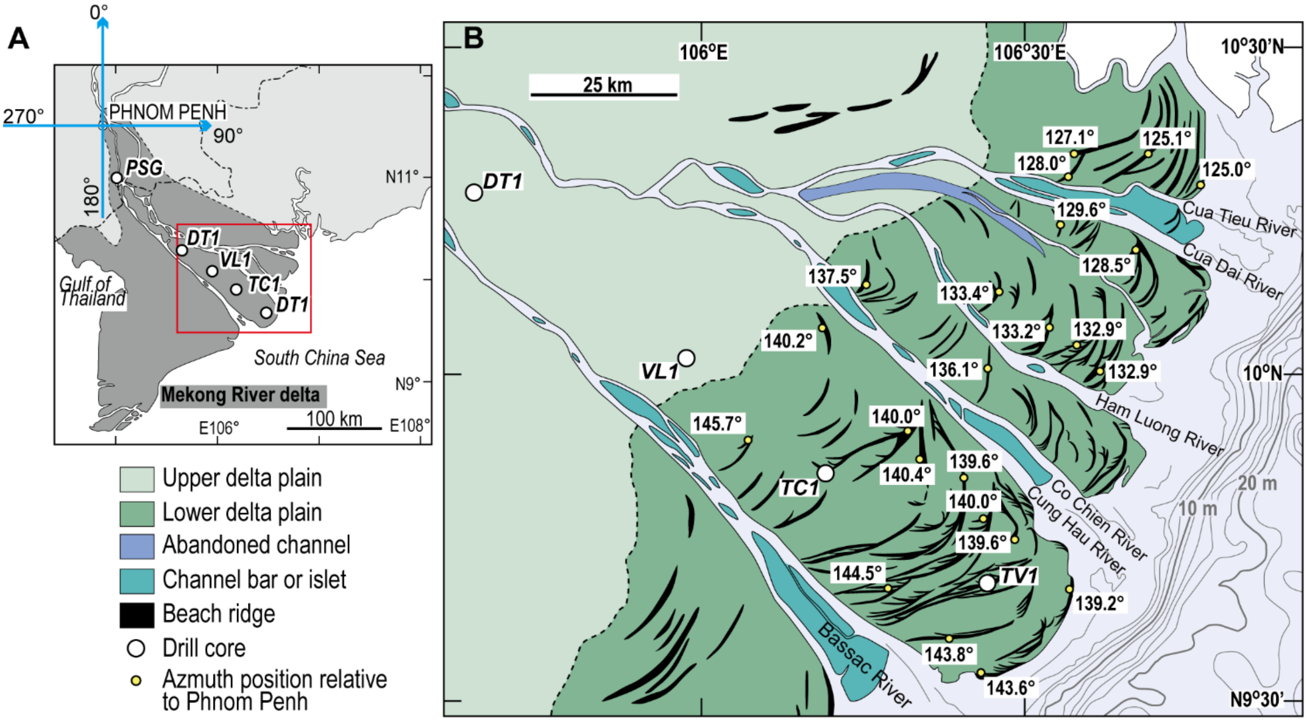


Figure DR2. Beach ridge system of the Mekong River delta. A: Location of Mekong River delta. Locations of sediment drill cores used in this study are also shown. The blue crossed arrows set a coordinate system, where the junction is located at Phnom Penh. The red rectangle identifies the location shown on Figures DR2B and 2B. B: Azimuths of beach ridges relative to Phnom Penh (after Tamura et al., 2012).