Title: The role of saltwater and waves in continental shelf formation: seaward-migrating clinoform

Short title: Role of saltwater and waves in continental shelf formation

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Abstract:

Continental shelves have generally been interpreted as drowned coastal plains associated with the allogenic effect of sea level variation. Here, without disputing this mechanism we describe an alternative autogenic mechanism for subaqueous shelf formation, driven by the presence of dissolved salt in seawater and surface waves. We use a numerical model describing flow hydrodynamics, sediment transport and morphodynamics in order to do this. More specifically, we focus on two major aspects; 1) the role of saltwater in the subaqueous construction of continental shelves, and 2) the transformation of these shelves into seaward-migrating clinoforms under the condition of repeated pulses of water and sediment input and steady wave effects, but no allogenic forcing such as sea level change. In the case for which the receiving basin contains fresh water of the same density as the sediment-laden river water, the hyperpycnal river water plunges to form a turbidity current that can run out to deep water. In the case for which the receiving basin contains sea water but the river contains sediment-laden fresh water, the hypopycnal river water forms a surface plume that deposits sediment proximally. This proximate proto-shelf can then grow to wave base, after which wave-supported turbidity currents can extend it seaward. The feature we refer is synonymous with near-shore mud belts.

Key words: continental shelves, dissolved salt, wave base, hypopycnal flows, mud belts

Significance statement:

Continental shelves have been generally interpreted to be coastal plains that have been drowned by sea level rise. Here we offer an alternative mechanism. Dissolved salt in seawater generally forces sediment-laden freshwater from rivers into surface water flows, from which sediment (mud) settles out in the near-shore zone. Over time, this platform can build up to wave base, constructing a shelf within a mud belt. Wave-induced sediment resuspension can drive the seaward extension of the shelf. This implies that changing sea level is not the only mechanism for building continental shelves.

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Introduction

Continental shelves are located at the buffer zone between the terrestrial and deep ocean environments. The morphology and morphodynamics of continental shelves has received significant attention in the fields of geology, engineering, and environmental science [e.g., 1-4]. However, the formational processes of continental shelves remain incompletely understood, in part because of the long-term geological processes associated with their formation and maintenance.

An important characteristic of continental shelves is their relatively shallow water depth (up to ~120 m at the shelf-slope break) [3]. Although this depth varies [5], it implies the presence of a dominant controlling factor determining both water depth and continental shelf formation. A common hypothesis is that continental shelves are drowned ancient coastal plains that formed during lowstands [3, 6, 7]. This general hypothesis implies that the shelf surface originally developed via long-term subaerial processes at lowstand, before being submerged by later sea level rise. According to this mechanism, the sediment on continental shelves is relict. This model gives a reasonable description of many shelves, such as that of the East Coast of the United States [e.g., 6, 8]. However, recent extensive investigations of continental shelves [e.g., 9] and proto-shelves [e.g., 10, 11] using stratigraphic measurements, isotopic analysis of deposited sediment, and drill-core samples imply that, even under the present high stand, shelves and proto-shelves can form and extend purely by a combination of subaqueous hydrodynamics, sediment transport, and morphodynamic processes. These shelves are typically characterized as mud belts or mud wedges (e.g. the Amazon mud belt [12], the northern Gulf of Mexico mud belt [11], and the Yellow Sea mud wedge [13]. Gao and Collins [14] report Holocene shelf mud deposits of up to 50 m in thickness. Indeed, much of the Italian Adriatic shelf clinoform was emplaced in the late Holocene under stillstand conditions (e.g., [15], Figure 3 of Maselli et al. [16]).

Steckler et al. [17] reconstructed the development of the New Jersey continental shelf based on seismic analysis and sequence stratigraphy, and showed clear clinoform migration and subsequent development of a continental shelf at long geological time scale. They also estimated paleo-water depths on the continental shelf, indicating that the clinoform rollover along the New Jersey continental margin has been submerged regardless of sea level. This suggests that the sea level difference between high stand and low stand cannot universally explain the hypothesis of continental shelves as being ancient coastal plains. Subaqueous processes (e.g., sediment supply [2], wave-, tide-, and wind-driven currents [18], and sediment re-distribution by turbidity currents [19, 20]) may also play important roles in the morphodynamics of continental shelves. In addition to sequence stratigraphy

[21], process-based approaches incorporating the concepts of morphodynamics or stratodynamics [e.g., 22] are crucial for a better understanding of the genesis of continental shelves.

Here, we present a formational mechanism for continental shelves that involves multiple interactions among terrigenous sediment supply, wave-current hydrodynamics, subaqueous sediment transport, and subsequent morphodynamic processes. The focus of this study concerns sedimentary continental shelves that have sediment deposition as the main formative driver (e.g., Cenozoic New Jersey passive margin [17]), rather than structural shelves, whose formation is determined by tectonic process (e.g., Quaternary active transform margin, central California [8]), or shelves governed by processes involving ice. More specifically, we demonstrate 1) the crucial role played by salt dissolved in ocean water in the formation of continental shelves, and 2) the long-term development of shelf morphology due to seaward-migrating clinoforms. Both these elements are intimately associated with interactions between fluvial suspended sediment supply, sediment deposition from hypopycnal plumes, and wave-induced sediment re-distribution on the shelf.

The transport characteristics of suspended load and/or mud supplied from rivers into a coastal ocean are key to understanding where sediment is deposited on the sea floor, and how sediment transport creates seascapes. Apart from rivers carrying unusually high sediment loads [23, 24], sediment-laden fresh river water is generally lighter than ambient salt water, preventing direct plunging of river water onto the sea bed. Instead, this density barrier results in the formation of a surface plume (hypopycnal flow) rather than a bottom current (hyperpycnal flow) [e.g., 25]. In this configuration, settling of fluvial sediment from plumes, and the subsequent development of weak turbidity currents may play dominant roles in the supply of river-derived sediment to continental shelves [e.g., 26, 27]. The differences in the way that hypo- and hyperpycnal flows move sediment and create morphology are significant; however, the effects of these different flow regimes on shelf morphology have not yet been clearly demonstrated.

We here consider a fresh water lake as a counterpoint to the ocean environment to illustrate the effects of hypo- and hyperpycnal flows on the morphodynamics of shelf-like morphology. Because sediment supply from rivers is thought to be a main driver of continental shelf formation [2], similar shelf morphology might be expected in ancient terrestrial lakes which have substantial fluvial sediment supply. However, shelf morphology in the form of a bench that connects delta to delta is rarely seen in lacustrine environments [e.g., 28, 29]. We hypothesize that this is due to the different hydrodynamics and sediment transport between the two environments associated with dissolved salt in ambient water.

Another focus of this research is to understand wave effects on the resuspension and redistribution of deposited sediment on the shelf, and the resulting shelf morphodynamics. Surface waves induced by storms, for example, cause movement of the water body only to a specified depth below the water surface (wave base). When sea floor elevation exceeds wave base, surface waves can generate a wave-induced bottom boundary layer, resulting in resuspension of deposited sediment and subsequent truncation of the shelf surface. Wave-base theory offers another powerful element for explaining the evolution of continental shelves [e.g., 30-33]. This hypothesis has, however, only limited implications for continental shelf genesis, in that it acts only when the shelf is above wave base. Wave base changes as sea level varies, so an extremely long period of constant sea level is required to truncate the entire surface of a shelf. The duration of the present sea level from the end of the last glaciation may not be sufficient for this [34]. Dietz and Menard [35] note that wave base is typically not deep enough to explain the sustained water depth on continental shelves. However, waves do play an important role in sediment redistribution on the shelf, and contribute to clinoform development even during the present-day highstand [e.g., 19, 20, 36]. This indicates that the wave effect is a key factor explaining continental shelf formation, which is attributed to seaward-migrating clinoforms.

In this study, we use a numerical model to investigate the formative mechanisms of continental shelves. The goal is to investigate the interaction between sediment dispersal due to hypopycnal flow, surface wave effects on the redistribution of deposited sediment on the continental margin, and shelf morphodynamics in terms of migrating clinoforms. The individual effects of each process on margin development have been studied through field observations, laboratory experiments, numerical modeling, and theoretical analysis [e.g., 11, 37-39]. However, because of the complexity of the system, the role of multiple interacting mechanisms on continental margin development remains under-investigated. The numerical model and calculational conditions are considerably simplified in this study (for example, alongshore processes are not included, *Methods*), but it still captures the essential complexities of the system suggested by previous studies. Our study provides the first description of autogenic continental shelf formation due to subaqueous hydrodynamics and sediment transport, in the absence of allogenic effects such as sea-level variation, tectonism, and changes in sediment supply rate.

Results

Morphodynamic differences between hypopycnal and hyperpycnal flows

The aim of our first numerical simulation is to determine the differences in shelf morphodynamic processes associated with hypo- and hyperpycnal flows. The initial bed geometry for this calculation represents an idealized, small continental margin of length 15 m, consisting of a low shelf, slope, and rise (see *SI Appendix*, *Fig.S*1). We imposed a fresh, sediment-laden water supply of constant water discharge and suspended sediment concentration from an upstream inlet surface layer. The key factor differentiating the two flow regimes in the simulations is the dissolved salt in the ambient water. To simulate a hypopycnal flow, we set the excess density of the ambient water due to dissolved salt at 40 kg/m^3, (so that the receiving basin mimics the ocean). This ambient water has a density that is larger than the excess density of the inflow water carrying suspended sediment. For the hyperpycnal flow cases, the excess density of the ambient water due to salt is set to be zero (i.e., the receiving basin mimics a freshwater lake), resulting in the direct plunging of the sediment-laden inflow water. This computational setting highlights the role of saltwater in the flow regime and subsequent shelf morphodynamics. Other calculation conditions and detailed computational settings are in *SI Appendix*, *Methods and Results*. We performed several numerical simulations by changing parameters (e.g., water discharge, sediment concentration etc.) for sensitivity analysis, but below we show the results of a typical case (Case 1 in *SI Appendix*, *Table-S*1).

Figures 1 and 2 show the simulation results for flow and sediment transport behavior generated by a hypopycnal flow (Figure 1) and a hyperpycnal flow (Figure 2) respectively. For the hyperpycnal flow, the inflowing sediment-laden fresh water immediately plunges to the bottom, generating a turbidity current (Fig. 2a-1). This flow efficiently delivers sediment to the rise region (Fig. 2a-3). Flow and sediment transport processes associated with hypopycnal flow are, however, quite different. The initial density relationship between the inflow and the ambient water satisfies a stable stratification condition in terms of total density, generating a positively buoyant, hypopycnal plume (Fig. 1a-1). The fresh water flows near the surface and eventually reaches the downstream end of the domain (Fig. 1b-3); however, suspended sediment does not follow this behavior. As shown in Fig. 1a-2, plumes develop underneath the surface plume, aiding removal of sediment from the surface plume. Because sediment has a finite settling velocity, the transport process differs between dissolved salt and suspended sediment. As sediment settles out it creates a heavy layer below the body of the plume ("nose region", [40, 41]). Here the sediment of the surface plume mixes with ambient salt water just below the surface plume. This layer is unstable in terms of total density because the sediment settles into saline water, being heavier than the saline water below or the fresh water above. This results in a Rayleigh-Taylor-type instability. This settling-driven convection generates a downward flow to the bed, removing sediment from the plume much faster than the settling velocity of individual sediment particles (scavenging [42]). Because of this sediment loss, the surface plume is free of suspended sediment near the downstream end (Fig. 1a-3). Instead, sediment removed from the hypopycnal plume generates a secondary hyperpycnal plume on the slope (Fig. 1a-3). These processes, namely, settling-driven convection occurring underneath a hypopycnal plume and subsequent formation of a secondary turbidity current, are also observed in some experimental studies [39, 43]. A comparison of the velocity fields between the two flow regimes (Figs. 1-3b and 2-3b) indicates that this secondary turbidity current is not as strong as the primary turbidity current of the hyperpycnal case. Sediment transport into the rise region due to this weak turbidity current is less intense than the hyperpycnal case. In addition, the potential for re-entrainment of sediment on the shelf is small in the hypopycnal case, which instead contributes to sediment deposition on the shelf and slope. This may indicate that the sediment mixing and turbidity current generated by hypopycnal flows have important roles in proximal sedimentation, but only limited effects on the flow and morphodynamics in the deep ocean. We illustrate below that this tendency to capture sediment proximally is one of the fundamental building blocks of continental shelves.

The hydrodynamics and sediment transport dynamics of hypo- and hyperpycnal flows result in different morphodynamic behavior of the shelf. Figure 3 shows the bed surface profiles obtained by hypo- and hyperpycnal flows in this case after 4 hours (4 one-hour events) of simulation. It shows that 1) hypopycnal flow contributes more proximal sediment deposition on the shelf than hyperpycnal flow, and 2) conversely, hyperpycnal flow transports more sediment onto the rise region than hypopycnal flow. In this simulation, the initial geometry of the shelf is horizontal for simplicity, so the depositional features of hyperpycnal flow are over-emphasized on the shelf region. Even so, the hyperpycnal flow cannot induce nearly as much sediment deposition on the shelf as the hypopycnal flow. The numerical results regarding sensitivity of modelled morphodynamics of the shelf show that this trend is universal to all the cases we tested (*SI Appendix, Results*).

These results show that, at least in our simplified model, hypopycnal flow contributes primarily to proximal deposition of supplied fluvial sediment on the shelf, whereas hyperpycnal flow predominantly carries sediment to the deep ocean. These features indicate that dissolved salt in the ambient water has an important role in controlling the fate and transport of sediment on the shelf, and thus shelf formation. However, the results also imply that hypopycnal flows themselves rarely induce erosion of deposited sediment on the shelf. If we were to continue the simulation for a sufficiently long time, the shelf region would eventually be filled with sediment, and be converted to coastal plain. Channelization cannot be captured in this 2D model but could be if extended to 3D [44].There thus needs to be a factor that limits deposition on the shelf. We identify this factor as wave action. As hypopycnal flows build up the shelf, the shelf surface eventually reaches wave base. Wave action can then create weak wave-supported turbidity currents that deliver sediment from the shelf to the rise, i.e., below wave base. This would allow for a near-bypass condition on the shelf, with a migrating clinoform at its outer edge.

Wave effects on the development of seaward-migrating clinoforms

Here, we focus on the case of hypopycnal flow in order to focus on continental shelf formation. This is because hyperpycnal flows contribute less to proximal sediment deposition on the shelf surface; this deposition is likely a key factor governing shelf extension. The computational conditions of this run are essentially the same as the calculation shown above, but some changes are made as follows. First, we extend the continental domain length from 15 m to 30 m (so the computational domain is 30 m long, but the computational grid size is maintained) and remove the initial shelf from the computational domain. This change allows a large accommodation space for sediment deposition, and shows whether the model itself generates shelf formation and development. Second, we include wave effects on sediment transport (specifically, sediment entrainment from the bed) based on linear wave theory (*SI Appendix, Methods, Eqs.* (*S*14)-(*S*19)). The important parameters of this model are the significant wave height (H_s) and the wave period (T_w). We set these as H_s = 0.05 m and T_w = 1 s, respectively. These values are quite large for our small, laboratory-scale flume, but the erosional force of waves associated with these parameters will indeed be shown to be balanced by the sediment supply rate onto the shelf. Third, the upstream boundary condition is changed to repeated pulse inputs instead of a steady discharge condition, so as to simulate river floods. One repeated cycle consists of two time periods: steady water supply with constant sediment concentration for a specified period (T_{flood}), and no water or sediment supply for another specified period (T_{wave}). Sediment supply (the depositional driver) occurs only in period T_{flood}, while the wave effect (the erosional driver) is superimposed throughout the entire calculation. In this computational setting, T_{flood} characterizes sediment supply during a flood event into the ocean, whereas T_{wave} characterizes resuspension of deposited sediment, and redistribution on the shelf during multiple dry storm events. In nature, floods and storms can coincide (wet storm) or occur separately (dry storm) [e.g., 20]. Here, we set T_{flood} and T_{wave} to be 1250 s and 20000 s, respectively. We determine the relationship between these time scales so as to satisfy a near-bypass condition on the shelf. In other words, in this model framework these time scales are imposed by the relationship between the sediment supply rate and wave energy.

The morphodynamics of the shelf generated in this scenario is shown in Fig. 4. This figure shows a time series of the bed surface in the run, a feature that helps describe stratigraphic architecture. Note that the interval between two lines in the figure represents the deposited sediment thickness between four repeated pulse inputs. At the early stage of the run, the sediment rainout from the hypopycnal plume contributes the proximal sediment deposition on the bottom bed, building up the shelf vertically. This shelf development is clearly recognized from the temporal change of position of the rollover point. During this stage, the bed surface of the shelf is well below the wave base associated with assumed wave energy, so that the surface waves play no role in shelf morphodynamics. However, aggradation of the shelf surface eventually results in the wave effect becoming significant. Figure 4 clearly shows that the rollover location starts shifting seaward when the shelf height reaches 0.75 m, a point at which waves start to play a role in subaqueous sediment transport. When the shelf becomes higher than wave base, the waves can entrain sediment deposited on the shelf. The entrained sediment generates a weak wave-supported turbidity current. This turbidity current redistributes sediment from the shelf region to the slope and rise regions. As a result, the shelf elongates in the seaward direction in the form of a migrating clinoform. Figure 4 suggests that shelf morphodynamics at this stage is attributed to the development of a clinoform of permanent form [39]. Figure 5 shows the temporal change in the slope of the slope region. The continental slope becomes steeper as the shelf aggrades, but its slope asymptotically reaches approximately 4° in the late stage of the simulation. This behavior might be caused by sediment deposition in the rise region (i.e., build-up of the basin bottom). Several mechanisms that limit the steepness of the slope such as internal waves [45] and submarine groundwater flow [1] are lacking in our model, but, 4° is nevertheless a reasonable value for continental slopes in nature [1, 46].

Another interesting result of this simulation is the development of sediment waves at the rollover of the modelled continental shelf. This type of morphodynamic feature has been clearly observed in seismic measurements of continental margins [15, 47, 48]. Figure 6 provides a more detailed view of the development of sediment waves during three repeated pulse inputs. The sediment waves tend to develop below the rollover, where the slope is approximately the steepest value in the simulated continental slope region. These waves migrate slightly to the landward side, but also disappear when they reach the shelf. As shown in Fig. 6, the wave effect imposed during the entire calculation causes a bottom turbidity current (thin density layer). This turbidity current plays an important role in the formation of the sediment waves of Figure 6. The flow features over the sediment waves likely show the presence of internal hydraulic jumps, as shown in Figs. 6b, d, and f. This upstream migration of sediment waves bounded by hydraulic jumps induced by a bottom turbidity current appears to be another case of deepwater mudwave cyclic steps [49]. The disappearance of these waves at the shelf-slope break may be due to the large amount of sediment supply from hypopycnal flow, which aggrades the bed and buries the waves. This aggradational tendency is much stronger near the distal end of the shelf than in the slope region because the slope of the shelf surface is gentler than the slope region. These effects cause repeated cycles of formation and disappearance of sediment waves near the rollover of the shelf.

Continental shelves have most commonly been interpreted as ancient alluvial or coastal plains, with sea level variation and subsequent transgression necessary for their development [e.g., 3]. However, the simulation results clearly indicate that, even under steady discharge and sediment supply and a stillstand condition, a self-evolving continental shelf associated with seaward migrating clinoforms is possible.

Discussion

The numerical results of this study indicate that a combination of hypopycnal sediment supply and wave action can lead to the formation of a continental shelf as a seaward-migrating clinoform. This combination of two factors is important to the formation of shelf morphology. If one of them is missing, subsequent shelf morphology may be greatly different or even not realized. Hyperpycnal flows contribute less to proximal sedimentation on the shelf, so that shelf sediment is less available for redistributing on the clinoform by wave action than hypopycnal flows. If waves are not considered, the shelf height rises to the point that it is exposed, eventually resulting in a new coastal plain. However, the physical phenomena described in the model are highly simplified. Below, we discuss how these simplifications affect the results and interpretation, as well as the implications of the numerical results for natural continental shelf formation.

The results indicate a purely autogenic mechanism for continental shelf formation associated with seaward-migrating clinoforms driven by subaqueous morphodynamic processes. While we do not say that our mechanism is the only one for shelf formation, we emphasize that it needs no allogenic forcing such as sea level change. Many previous studies based on sequence stratigraphy have shown that allogenic effects of tectonism and sea level variation on continental shelf morphology are important, and in some cases they play dominant roles in shelf genesis [3]. The formation and development of continental shelves is a long-term process occurring at geological timescales. Thus, long-term allogenic effects and short-term autogenic processes can be expected to interact with each other. The autogenic effects analyzed in this study thus may be superimposed on allogenic effects, such as the significant effect of waves observed in the simulations to plane off the shelf and drive seaward clinoform migration. For example, the constant sea level adopted in the simulation forces vertical development of the shelf, eventually resulting in seaward clinoform migration without shelf aggradation/degradation [21]. This clinoform development likely leads a convex-up trajectory of the rollover point, as shown in Fig. 4. A concave-up trajectory of the rollover point is also commonly observed at plate margins [e.g., 3]. Sea-level variation changes wave base, so the shelf surface of this model should be expected to rise or fall accordingly, as long as sediment supply is commensurate to fill accommodation space so created. Sea level rise allows sustained vertical development of the shelf. If waves plays a role in sediment transport at the seafloor during sea level rise, the clinoform will migrate seaward. Vertical development of the shelf with a migrating clinoform (i.e., sigmoid progradation [21]) may result in a concave up trajectory of the rollover. Such allogenic-autogenic interactions need to be investigated further in the future; our results, which focus on autogenic effects, can help distinguish their relative contributions to the genesis of continental shelves [50].

Another limitation is the scale of the numerical simulation, which is here performed on a small scale. We may scale up the numerical results by means of Froude scale similarity, a method which has been effective for engineering-scale models. Although this similarity rule cannot give in truly scale-invariant results for turbidity current dynamics, the scale effect on depositional turbidity currents, i.e. the weak wave-supported turbidity current associated with hypopycnal flow observed in our simulations, may not be very significant [51]. However, it is useful to discuss scale effects on other physical phenomena, e.g., the convection instability seen at the interface between a surface sediment-laden freshwater plume and salt-rich ambient water below.

The densimetric Froude number, F_{rd}, is defined in terms of the upstream inlet conditions as follows.

$$F_{rd} = \frac{U_{inlet}}{\sqrt{\gamma g C_{inlet} H_{inlet}}} \tag{1}$$

where H_{inlet}, C_{inlet} and U_{inlet} are the flow thickness, volumetric suspended sediment concentration and flow velocity of inflow water at the inlet, respectively. Also g is the gravitational acceleration and γ is the specific weight of sediment in water, i.e., $\gamma = (\rho_c - \rho)/\rho$, where ρ_c and ρ are the density of sediment and water, respectively. Froude similarity is satisfied when the value of F_{rd} of the model (F_{rdm}) is equal to the corresponding value of the prototype (F_{rdp}) i.e., $F_{rdm} = F_{rdp}$. Note that we assume the same suspended sediment concentration and specific weight of sediment between the model and the prototype. This dynamic similarity then constrains the relationship between the kinematic similarity parameter, λ_v, which represents the velocity ratio between the model and the prototype, i.e., $\lambda_v = V_p/V_m$, and the geometric similarity parameter, λ_L, which represents the length ratio between the model and the prototype, i.e., $\lambda_L = L_p/L_m$, as follows.

$$\lambda_v = \lambda_L^{1/2} \tag{2}$$

An appropriate length scale that characterizes continental shelves is the sustained water depth on the shelf itself; we may be able to determine the geometric similarity based on this water depth. In the simulation, the sustained water depth on the shelf is approximately 0.2 m, yet this depth in nature is generally around 100 m. This gives $\lambda_L = 500$ and $\lambda_v = 22.2$. The length scale of the numerical simulation can be upscaled using this geometric similarity. The modeled clinoform relief height is approximately 0.8 m, as shown in Fig. 4, resulting in an upscaled value of 400 m. This is a relatively small-scale clinoform relief for the continental shelf, as seen in the New Jersey margin [17], but is still larger than "platform" scale, which is a small-scale shelf like morphology generally observed on a continental margin [3, 4]. It is also larger than the Western Adriatic shelf clinoform [15]. The simulated height of the clinoform is likely restricted by the initial depth of the basin (i.e., 1.2 m). In addition, the water depth seaward of the slope increases in nature, and this has an important effect on large-scale continental margin development [3]. The interplay of these limitations mean that the simulated shelf formation process might specifically correspond to the initial development of a continental shelf in the near-shore region.

In contrast to the geometric upscaling above, we now use a different sediment upscaling method, that of Imran et al. [51]. First, the fall velocity in the model, v_{sm}, is scaled up by means of kinematic similarity, i.e., $v_{sp} = \lambda_v v_{sm}$. The sediment diameter is then back-calculated using a formula estimating the settling velocity w_f. Here, we use the Stokes settling velocity for simplicity. This upscaling gives the following relationships. The density flow is characterized as Froude subcritical (F_{rd}=0.82) at the inlet, and the inlet Reynolds number, Re, is 3.7×10^7. The upscaled sediment diameter is approximately 0.1 mm, which reasonably corresponds to fine-grained suspended sediment. For this size of sediment, settling-driven convection may be dominant rather than double-diffusive convection, which is caused by the difference in molecular diffusivity between salt and fine sediment, in forming the interfacial instability beneath the hypopycnal plume [52] (see details in *SI Appendix*, *Methods*). The upscaled wave characteristics (i.e., significant wave height of 25 m, and the wave period of 22 sec) are somewhat extreme, and could exceed typical storm weather conditions. However, the wave characteristics and the two time periods, which represent sediment supply and wave-dominated periods (i.e., T_{flood} and T_{wave}), have been chosen to achieve sediment bypass conditions on the shelf. Limited computational resources constrain the computational time, so the time scales must be relatively short and the wave characteristics must be extreme in the model. In natural environments, the dominant wave height and period are dependent on the geographic region and climate, affecting wave base and thus shelf geometry [32]. In addition, the return period of the waves considered here also depends on the dominant wave intensity, affecting the relation between the timescale of sediment supply (depositional driver) and that of the wave-induced sediment redistribution (erosional driver). This might be one of the factors causing substantial variation of water depth over the continental shelves on the Earth [5]. Future development of computational power will relax the model limitations described above, and will help to set more reasonable computational conditions for modeling shelf morphodynamics.

Our numerical simulations indicate that settling-driven (and double diffusive) convection associated with fingering play an important role in controlling the transport and fate of sediment associated with hypopycnal flows. Yet, a substantial model limitation is involved in capturing the nature of this density convection. This convection is a very small-scale phenomenon (*SI Appendix Methods*); thus, in principle, a numerical approach suitable to capturing it would involve DNS or LES [27, 38, 40]. Although we capture some of the relevant convection characteristics in the present model, it appears that the size of the generated plume and downward density flow formed as a result is grid-dependent in the simulation. In addition to this, the Reynolds-averaged approach we use here is not able to capture some of important physical mechanisms of this phenomenon. For example, the turbulent diffusivity modelled in Reynolds-averaged approach is generally larger than the molecular diffusivity. The density convection between the surface plume and the ambient water in the simulation is mainly driven by settling convection, with the double diffusive effect forced to become negligibly small. Such model limitations regarding the resolution of fingering is a constraint to field-scale applications of the model. This is one reason why we perform our simulations in at small-scale. A submodel that expresses the net sedimentation rate (or net fall velocity) from the hypopycnal plume, will be essential for including this effect in large-scale models. A parameter study based on a dataset obtained via DNS [41] can provide useful insight in this regard. The importance of double diffusive convection (i.e., salt fingers, [56]) was first recognized in stratified thermohaline systems (e.g., Thermohaline Staircases) [57-59]. The problem has been pursued more recently in terms of numerical modeling and experiments in a sediment-salt system [27, 38, 41], so that this effect will be included in large-scale models as incorporated in models of thermohaline systems [e.g., 60]. But it should be realized that these fingering features are fragile, and may in the field be broken up to larger-scale features by ambient turbulence. The same may not be true of flocs [53, 54, 55], a model of which is difficult to implement at the present model scale. Detailed field observations coupled with the numerical modelling will be a significant challenge in this regard.

In the simulation, we neglect the alongshore dimension to simplify the problem and reduce computational time. Flow and sedimentation patterns may differ substantially in a three-dimensional basin. The alongshore dispersal of sediment is an important factor for the behavior of positively buoyant, hypopycnal plumes [25]. This lateral sediment dispersal of a hypopycnal plume associated with a river mouth (i.e., point source) greatly affects the sedimentation rate on the shelf. Neglecting the lateral dimension in our simulation may overestimate the sedimentation rate on the shelf. But as Cattaneo et al. [61] have shown in the Adriatic Sea (Figure 4 therein), geostropic processes can meld a line of point sources into an effective line source, to which this model is applicable. Alongshore sediment dispersal is also important for the flow field underneath the hypopycnal plume. For instance, Henniger and Kleiser [27] performed large eddy simulations of the dynamics of hypopycnal plumes in a small three-dimensional basin. They showed that, because of the limitation of the model domain, a backward reverse flow (from seaward to landward) was generated.

Such a flow may exist in nature, but lateral dispersal of the flow will suppress this flow pattern.

In addition to the flow field, the simulated morphodynamic features of the shelf will be affected by the alongshore dimension. Sediment transport to the continental slope due to the wave-induced turbidity current migrates the shelf clinoform seaward, and develops sediment waves near the rollover. This result suggests the formation of a strongly aggradational feature on the modeled continental slope. If the alongshore dimension is considered, surface waves may force a more horizontal 2D wave-supported turbidity current rather than a line-type current. When such a 2D turbidity current reaches the shelf break, it may migrate the clinoform, but there is also a possibility for flow focusing and the formation of submarine gullies [43]. Furthermore, as mentioned in the results, a turbidity current flowing along a continental slope may also causes the formation of a submarine fan system [62]. These different morphodynamic processes are expected to coexist during formation of a continental shelf.

Conclusion

In this study, we perform numerical simulations of continental-shelf formation. We focus on two major aspects: 1) the role of saltwater in developing continental shelves, and 2) self-evolving continental shelf formation with seaward-migrating clinoforms. We perform our analysis with repeated pulses of water and sediment input into the nearshore zone, but steady wave effects, and without allogenic effects such as sea level change. There is a common understanding according to which many continental shelves are essentially submerged coastal plains formed during low stand. Our results suggest an additional, autogenic mechanism for continental shelf formation or augmentation by purely subaqueous morphodynamic processes.

The first aspect of this study is intended to highlight the importance of dissolved salt in ambient water on the transport and fate of terrigenous suspended sediment. The numerical results clearly show different behaviors between hypo and hyperpycnal flows (i.e., with and without dissolved salt in ambient water) on the simulated morphodynamics of shelf morphology. Hypopycnal flow shows purely depositional features in shelf development. In this flow regime, sediment-laden fresh river water overlies salty ambient water in a condition of stable stratification in terms of the total density of fluid. However, because of the fall velocity of sediment, an interfacial instability develops between the two layers, resulting in significant sediment loss from the surface hypopycnal plume. This sediment rainout subsequently contributes to the development of a weak turbidity current on the bottom. Such a weak current is found to be unable to entrain sediment from the bottom, so that this flow condition contributes purely to proximal deposition of sediment, and the formation of shelf morphology. On the contrary, hyperpycnal conditions generate a relatively strong density flow on the bottom. This current may cause erosion or deposition of sediment on the shelf, but most of the sediment is delivered into deep water. These results indicate that dissolved salt plays an important role in controlling sediment dispersal, and in suppressing direct delivery to deep water.

The depositional features of hypopycnal flows are key for explaining the large amount of sediment supply to the continental shelf. Another factor for continental shelf formation is the effect of waves on the redistribution of deposited sediment on the shelf. We find that, if a strong surface wave effect is imposed for a time period sufficient to flush out sediment deposited by hypopycnal flows down to wave base (i.e., to a bypass condition), then continental shelf development with a seaward-migrating clinoform can be achieved. Wave energy resuspends sediment from the bed, and the subsequent development of a wave-supported turbidity current brings sediment from the shelf to the slope, where it deposits below wave base. This contributes to seaward migration of the clinoform. Conversely, sediment resuspension due to waves restricts further vertical accumulation of sediment on the shelf, resulting in a sustained water depth on the shelf associated with the level of wave base. These subaqueous hydrodynamic, sediment-transport, and morphodynamic processes lead to continental shelf development with a migrating clinoform, even under conditions of constant sea level.

In nature, autogenic subaqueous factors associated with the morphodynamics of continental shelves (internal forces) are superimposed on other allogenic processes, such as sea-level variation and tectonism. The relationship between autogenic and allogenic effects should be clarified in future work, because sea-level variation and tectonism are known to have played important roles in the formation of continental shelves [3]. However, in so far as subaqueous processes have received less attention in the context of continental-shelf morphodynamics, our results provide new insight and interpretations of the genesis of continental shelves.

Methods

The system modeled in this study (i.e., dynamics of hypo- and hyperpycnal flows and subsequent morphodynamics of continental shelves) is complex and multiscaled in both time and space. It is unreasonable to treat all the physics above in a precise way using high-resolution physics-based numerical model at geological time scales, so we need several simplifications (see more detail in *SI Appendix Methods*). Here, we perform numerical simulations at a laboratory-scale, vertical two-dimensional field (cross-shore only). The density-driven flow is calculated by an unsteady Reynolds-averaged Navier-Stokes model with k-ε type turbulent closure. Stratification effects on turbulence production are also considered. The transport equation (advection-diffusion equation) is used to calculate the suspended sediment transport and dissolved salt in the fluid. Both sediment and salt contribute to the density of the fluid, whereas the temperature effect is neglected in our model. The sediment is treated as a single-grain cohesionless sediment. To include the effect of surface waves on sediment transport, we use a simple linear wave theory. More specifically, the additional shear stress due to the presence of a wave boundary layer is calculated using a linear wave theory. The details of the model and results are described in SI Appendix, and the code and calculation data used in the paper can be accessed at the Figshare database [63].

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Figure Captions

Figure 1. Simulation results of hypopycnal flow in Case 1: a) suspended sediment transport expressed by the excess density due to sediment; b) dissolved salt transport expressed by the excess density due to salt; and c) magnitude of flow velocity.

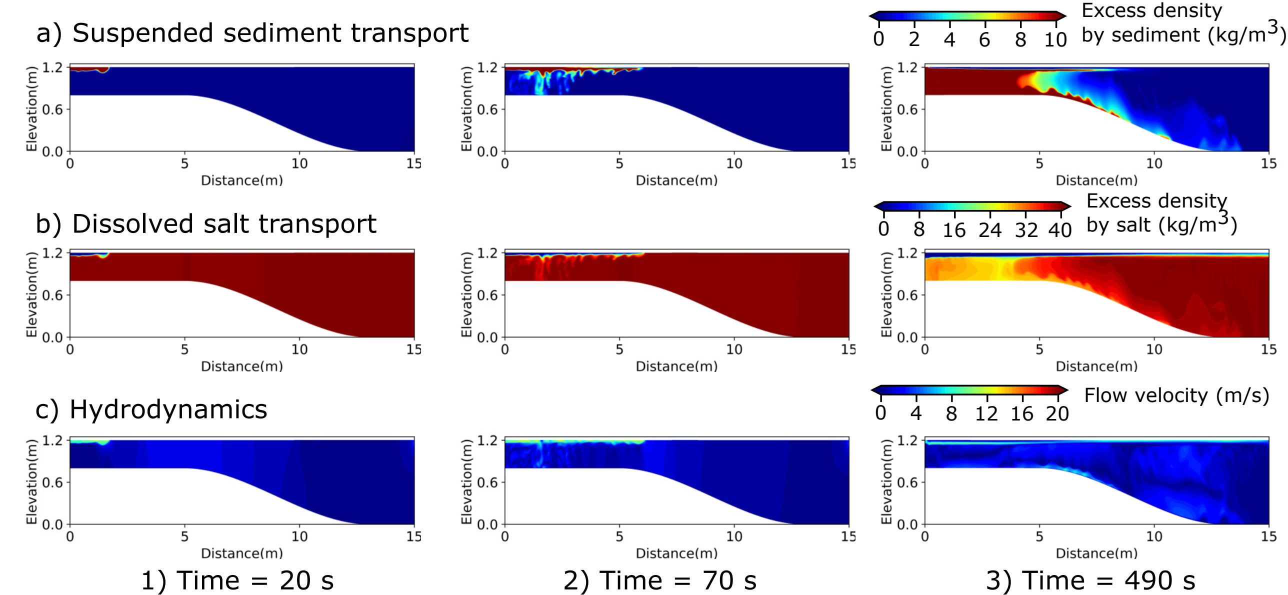
Figure 2. Simulation results of hyperpycnal flow in Case 1: a) suspended sediment transport expressed as excess density due to sediment; and b) magnitude of flow velocity.

Figure 3. Bed surface profiles developed by the hypo- and hyperpycnal flows of Case 1 (see *SI Table-S*1) after 4 hours of simulation.

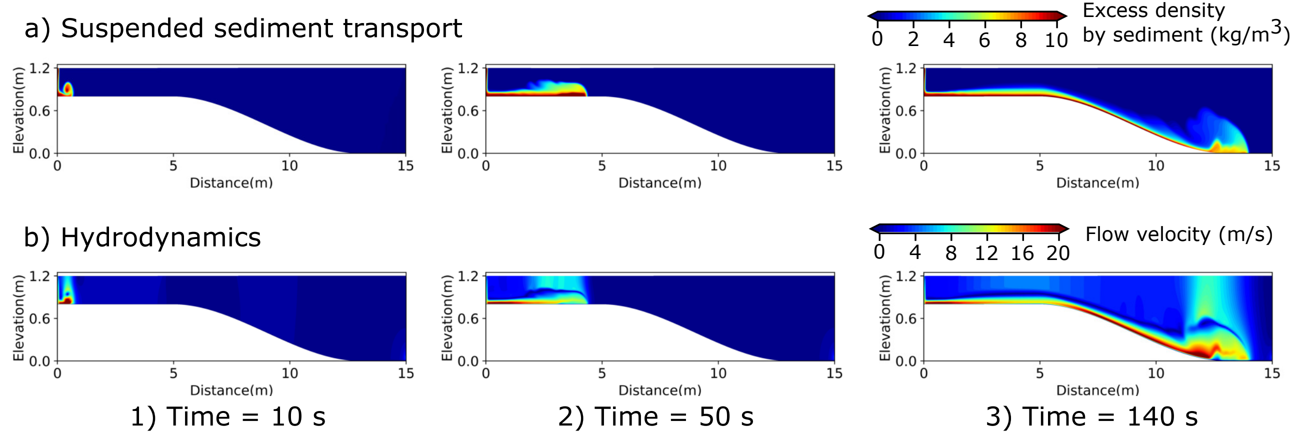
Figure 4. Computational result of shelf morphology development without an initial proto-shelf. The time interval between each line represents the time between four repeated pulse inputs, i.e., $4(T_{flood} + T_{wave})$. The blue points denote the rollover point, which is determined by the maximum curvature of shelf morphology, and the solid black line shows the time change of position of the rollover points.

Figure 5. Temporal change in modelled continental slope steepness corresponding to the case of Figure 4.

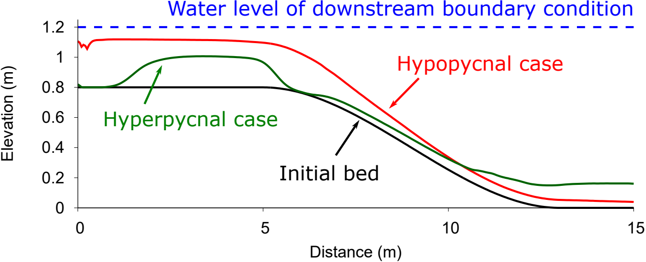
Figure 6. Development of sediment waves at the shelf rollover through three repeated pulse inputs.



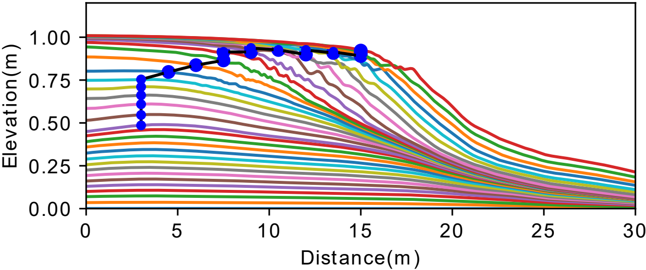
a) Suspended sediment transport
Excess density by sediment (kg/m3)
0 2 4 6 8 10
b) Dissolved salt transport
Excess density by salt (kg/m3)
0 8 16 24 32 40
c) Hydrodynamics
Flow velocity (m/s)
0 4 8 12 16 20
Elevation(m)
Distance(m)
1) Time = 20 s
2) Time = 70 s
3) Time = 490 s



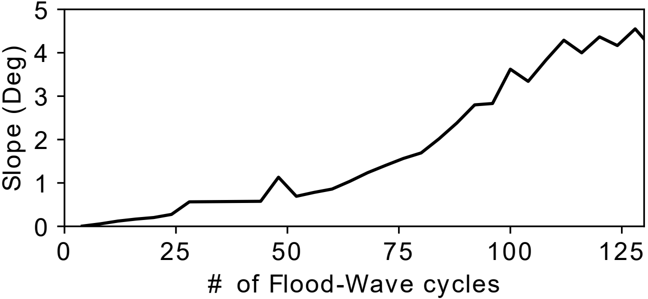
a) Suspended sediment transport
Excess density by sediment (kg/m3)
0 2 4 6 8 10
b) Hydrodynamics
Flow velocity (m/s)
0 4 8 12 16 20
Elevation(m)
1.2
0.6
0.0
Distance(m)
0 5 10 15
1) Time = 10 s
2) Time = 50 s
3) Time = 140 s



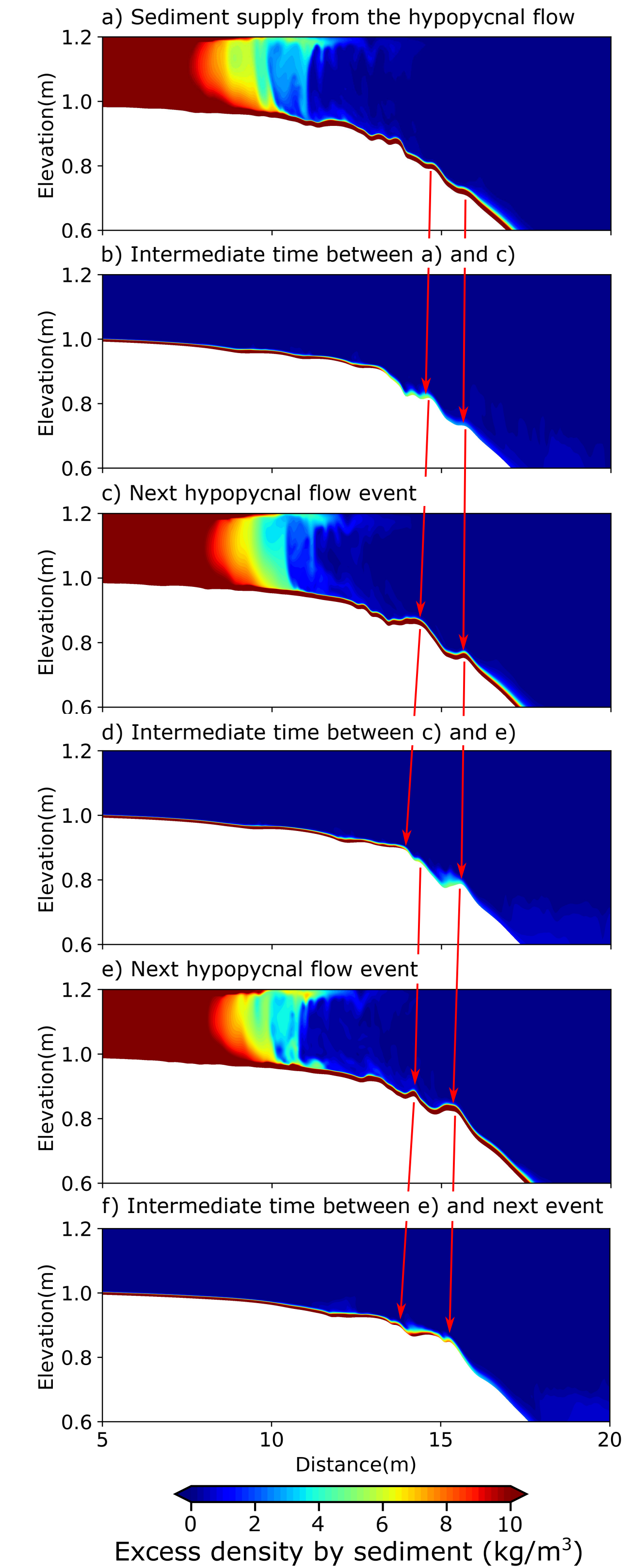
Water level of downstream boundary condition
Hypopycnal case
Hyperpycnal case
Initial bed
Elevation (m)
Distance (m)
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15



Elevation(m)
1.00
0.75
0.50
0.25
0.00
0
5
10
15
20
25
30
Distance(m)



Slope (Deg)
0
1
2
3
4
5
0
25
50
75
100
125
# of Flood-Wave cycles



a) Sediment supply from the hypopycnal flow
b) Intermediate time between a) and c)
c) Next hypopycnal flow event
d) Intermediate time between c) and e)
e) Next hypopycnal flow event
f) Intermediate time between e) and next event
Elevation(m)
1.2
1.0
0.8
0.6
5
10
15
20
Distance(m)
0
2
4
6
8
10
Excess density by sediment (kg/m^3)