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19 Abstract:

Continental shelves have generally been interpreted as drowned coastal plains 20associated with the allogenic effect of sea level variation. Here, without disputing this 21mechanism we describe an alternative autogenic mechanism for subaqueous shelf 22formation, driven by the presence of dissolved salt in seawater and surface waves. 23We use a numerical model describing flow hydrodynamics, sediment transport and 24morphodynamics in order to do this. More specifically, we focus on two major 25aspects; 1) the role of saltwater in the subaqueous construction of continental 26shelves, and 2) the transformation of these shelves into seaward-migrating clinoforms 27under the condition of repeated pulses of water and sediment input and steady wave 28effects, but no allogenic forcing such as sea level change. In the case for which the 29receiving basin contains fresh water of the same density as the sediment-laden river 30 water, the hyperpycnal river water plunges to form a turbidity current that can run 31out to deep water. In the case for which the receiving basin contains sea water but 32the river contains sediment-laden fresh water, the hypopycnal river water forms a 33 surface plume that deposits sediment proximally. This proximate proto-shelf can then 34grow to wave base, after which wave-supported turbidity currents can extend it 35seaward. The feature we refer is synonymous with near-shore mud belts. 36

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

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41 Significance statement:

Continental shelves have been generally interpreted to be coastal plains that have 42been drowned by sea level rise. Here we offer an alternative mechanism. Dissolved 43salt in seawater generally forces sediment-laden freshwater from rivers into surface 44water flows, from which sediment (mud) settles out in the near-shore zone. Over 45time, this platform can build up to wave base, constructing a shelf within a mud belt. 46Wave-induced sediment resuspension can drive the seaward extension of the shelf. 47This implies that changing sea level is not the only mechanism for building 48continental shelves. 49

50 **/body**

51

52 Introduction

53 Continental shelves are located at the buffer zone between the terrestrial and deep 54 ocean environments. The morphology and morphodynamics of continental shelves 55 has received significant attention in the fields of geology, engineering, and 56 environmental science [e.g., 1-4]. However, the formational processes of continental 57 shelves remain incompletely understood, in part because of the long-term geological 58 processes associated with their formation and maintenance.

An important characteristic of continental shelves is their relatively shallow 59water depth (up to ~120 m at the shelf-slope break) [3]. Although this depth varies 60 [5], it implies the presence of a dominant controlling factor determining both water 61 depth and continental shelf formation. A common hypothesis is that continental 62shelves are drowned ancient coastal plains that formed during lowstands [3, 6, 7]. 63 This general hypothesis implies that the shelf surface originally developed via 64 long-term subaerial processes at lowstand, before being submerged by later sea level 65rise. According to this mechanism, the sediment on continental shelves is relict. This 66 model gives a reasonable description of many shelves, such as that of the East Coast 67 of the United States [e.g., 6, 8]. However, recent extensive investigations of 68 continental shelves [e.g., 9] and proto-shelves [e.g., 10, 11] using stratigraphic 69 measurements, isotopic analysis of deposited sediment, and drill-core samples imply 70

that, even under the present high stand, shelves and proto-shelves can form and 71extend purely by a combination of subaqueous hydrodynamics, sediment transport, 72and morphodynamic processes. These shelves are typically characterized as mud 73belts or mud wedges (e.g. the Amazon mud belt [12], the northern Gulf of Mexico 74mud belt [11], and the Yellow Sea mud wedge [13]. Gao and Collins [14] report 75Holocene shelf mud deposits of up to 50 m in thickness. Indeed, much of the Italian 76Adriatic shelf clinoform was emplaced in the late Holocene under stillstand conditions 77(e.g., [15], Figure 3 of Maselli et al. [16]). 78

Steckler et al. [17] reconstructed the development of the New Jersey 79continental shelf based on seismic analysis and sequence stratigraphy, and showed 80 clear clinoform migration and subsequent development of a continental shelf at long 81 geological time scale. They also estimated paleo-water depths on the continental 82 shelf, indicating that the clinoform rollover along the New Jersey continental margin 83 has been submerged regardless of sea level. This suggests that the sea level 84 difference between high stand and low stand cannot universally explain the 85 hypothesis of continental shelves as being ancient coastal plains. Subaqueous 86 processes (e.g., sediment supply [2], wave-, tide-, and wind-driven currents [18], and 87 sediment re-distribution by turbidity currents [19, 20]) may also play important roles 88 in the morphodynamics of continental shelves. In addition to sequence stratigraphy 89

[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 93involves multiple interactions among terrigenous sediment supply, wave-current 94 hydrodynamics, subaqueous sediment transport, and subsequent morphodynamic 95 processes. The focus of this study concerns sedimentary continental shelves that have 96 sediment deposition as the main formative driver (e.g., Cenozoic New Jersey passive 97 margin [17]), rather than structural shelves, whose formation is determined by 98 tectonic process (e.g., Quaternary active transform margin, central California [8]), or 99shelves governed by processes involving ice. More specifically, we demonstrate 1) the 100crucial role played by salt dissolved in ocean water in the formation of continental 101 shelves, and 2) the long-term development of shelf morphology due to 102seaward-migrating clinoforms. Both these elements are intimately associated with 103interactions between fluvial suspended sediment supply, sediment deposition from 104hypopycnal plumes, and wave-induced sediment re-distribution on the shelf. 105

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 109generally lighter than ambient salt water, preventing direct plunging of river water 110 onto the sea bed. Instead, this density barrier results in the formation of a surface 111 plume (hypopycnal flow) rather than a bottom current (hyperpycnal flow) [e.g., 25]. 112In this configuration, settling of fluvial sediment from plumes, and the subsequent 113114development 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 115that hypo- and hyperpycnal flows move sediment and create morphology are 116significant; however, the effects of these different flow regimes on shelf morphology 117have not yet been clearly demonstrated. 118

We here consider a fresh water lake as a counterpoint to the ocean 119environment to illustrate the effects of hypo- and hyperpycnal flows on the 120morphodynamics of shelf-like morphology. Because sediment supply from rivers is 121thought to be a main driver of continental shelf formation [2], similar shelf 122morphology might be expected in ancient terrestrial lakes which have substantial 123fluvial sediment supply. However, shelf morphology in the form of a bench that 124connects delta to delta is rarely seen in lacustrine environments [e.g., 28, 29]. We 125hypothesize that this is due to the different hydrodynamics and sediment transport 126between the two environments associated with dissolved salt in ambient water. 127

Another focus of this research is to understand wave effects on the 128resuspension and redistribution of deposited sediment on the shelf, and the resulting 129shelf morphodynamics. Surface waves induced by storms, for example, cause 130movement of the water body only to a specified depth below the water surface (wave 131base). When sea floor elevation exceeds wave base, surface waves can generate a 132wave-induced bottom boundary layer, resulting in resuspension of deposited 133sediment and subsequent truncation of the shelf surface. Wave-base theory offers 134another powerful element for explaining the evolution of continental shelves [e.g., 13530-33]. This hypothesis has, however, only limited implications for continental shelf 136genesis, in that it acts only when the shelf is above wave base. Wave base changes as 137sea level varies, so an extremely long period of constant sea level is required to 138truncate the entire surface of a shelf. The duration of the present sea level from the 139end of the last glaciation may not be sufficient for this [34]. Dietz and Menard [35] 140note that wave base is typically not deep enough to explain the sustained water 141depth on continental shelves. However, waves do play an important role in sediment 142redistribution on the shelf, and contribute to clinoform development even during the 143present-day highstand [e.g., 19, 20, 36]. This indicates that the wave effect is a key 144factor explaining continental shelf formation, which attributed is to 145seaward-migrating clinoforms. 146

In this study, we use a numerical model to investigate the formative 147mechanisms of continental shelves. The goal is to investigate the interaction between 148sediment dispersal due to hypopycnal flow, surface wave effects on the redistribution 149of deposited sediment on the continental margin, and shelf morphodynamics in 150terms of migrating clinoforms. The individual effects of each process on margin 151development have been studied through field observations, laboratory experiments, 152numerical modeling, and theoretical analysis [e.g., 11, 37-39]. However, because of 153the complexity of the system, the role of multiple interacting mechanisms on 154continental margin development remains under-investigated. The numerical model 155and calculational conditions are considerably simplified in this study (for example, 156alongshore processes are not included, *Methods*), but it still captures the essential 157complexities of the system suggested by previous studies. Our study provides the first 158description of autogenic continental shelf formation due to subaqueous 159hydrodynamics and sediment transport, in the absence of allogenic effects such as 160sea-level variation, tectonism, and changes in sediment supply rate. 161

162

163 **Results**

164 Morphodynamic differences between hypopycnal and hyperpycnal flows

165 The aim of our first numerical simulation is to determine the differences in shelf

morphodynamic processes associated with hypo- and hyperpycnal flows. The initial 166bed geometry for this calculation represents an idealized, small continental margin of 167length 15 m, consisting of a low shelf, slope, and rise (see SI Appendix, Fig.S1). We 168imposed a fresh, sediment-laden water supply of constant water discharge and 169suspended sediment concentration from an upstream inlet surface layer. The key 170171factor 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 172ambient water due to dissolved salt at 40 kg/m³, (so that the receiving basin mimics 173the ocean). This ambient water has a density that is larger than the excess density of 174the inflow water carrying suspended sediment. For the hyperpycnal flow cases, the 175excess density of the ambient water due to salt is set to be zero (i.e., the receiving 176basin mimics a freshwater lake), resulting in the direct plunging of the 177sediment-laden inflow water. This computational setting highlights the role of 178saltwater in the flow regime and subsequent shelf morphodynamics. Other 179calculation conditions and detailed computational settings are in SI Appendix, 180Methods and Results. We performed several numerical simulations by changing 181 parameters (e.g., water discharge, sediment concentration etc.) for sensitivity 182analysis, but below we show the results of a typical case (Case 1 in SI Appendix, 183Table-S1). 184

Figures 1 and 2 show the simulation results for flow and sediment transport 185behavior generated by a hypopycnal flow (Figure 1) and a hyperpycnal flow (Figure 2) 186respectively. For the hyperpycnal flow, the inflowing sediment-laden fresh water 187immediately plunges to the bottom, generating a turbidity current (Fig. 2a-1). This 188flow efficiently delivers sediment to the rise region (Fig. 2a-3). Flow and sediment 189transport processes associated with hypopycnal flow are, however, guite different. 190The initial density relationship between the inflow and the ambient water satisfies a 191stable stratification condition in terms of total density, generating a positively 192buoyant, hypopycnal plume (Fig. 1a-1). The fresh water flows near the surface and 193eventually reaches the downstream end of the domain (Fig. 1b-3); however, 194suspended sediment does not follow this behavior. As shown in Fig. 1a-2, plumes 195develop underneath the surface plume, aiding removal of sediment from the surface 196plume. Because sediment has a finite settling velocity, the transport process differs 197between dissolved salt and suspended sediment. As sediment settles out it creates a 198heavy layer below the body of the plume ("nose region", [40, 41]). Here the sediment 199 of the surface plume mixes with ambient salt water just below the surface plume. 200This layer is unstable in terms of total density because the sediment settles into saline 201water, being heavier than the saline water below or the fresh water above. This 202results in a Rayleigh-Taylor-type instability. This settling-driven convection generates a 203

downward flow to the bed, removing sediment from the plume much faster than the 204settling velocity of individual sediment particles (scavenging [42]). Because of this 205sediment loss, the surface plume is free of suspended sediment near the downstream 206end (Fig. 1a-3). Instead, sediment removed from the hypopycnal plume generates a 207secondary hyperpycnal plume on the slope (Fig. 1a-3). These processes, namely, 208209 settling-driven convection occurring underneath a hypopycnal plume and subsequent formation of a secondary turbidity current, are also observed in some experimental 210studies [39, 43]. A comparison of the velocity fields between the two flow regimes 211(Figs. 1-3b and 2-3b) indicates that this secondary turbidity current is not as strong as 212the primary turbidity current of the hyperpycnal case. Sediment transport into the 213rise region due to this weak turbidity current is less intense than the hyperpycnal case. 214In addition, the potential for re-entrainment of sediment on the shelf is small in the 215hypopycnal case, which instead contributes to sediment deposition on the shelf and 216slope. This may indicate that the sediment mixing and turbidity current generated by 217hypopycnal flows have important roles in proximal sedimentation, but only limited 218effects on the flow and morphodynamics in the deep ocean. We illustrate below that 219this tendency to capture sediment proximally is one of the fundamental building 220blocks of continental shelves. 221

222

The hydrodynamics and sediment transport dynamics of hypo- and

hyperpycnal flows result in different morphodynamic behavior of the shelf. Figure 3 223shows the bed surface profiles obtained by hypo- and hyperpycnal flows in this case 224after 4 hours (4 one-hour events) of simulation. It shows that 1) hypopycnal flow 225contributes more proximal sediment deposition on the shelf than hyperpycnal flow, 226and 2) conversely, hyperpychal flow transports more sediment onto the rise region 227than hypopycnal flow. In this simulation, the initial geometry of the shelf is horizontal 228for simplicity, so the depositional features of hyperpycnal flow are over-emphasized 229on the shelf region. Even so, the hyperpychal flow cannot induce nearly as much 230sediment deposition on the shelf as the hypopycnal flow. The numerical results 231regarding sensitivity of modelled morphodynamics of the shelf show that this trend is 232universal to all the cases we tested (SI Appendix, Results). 233

These results show that, at least in our simplified model, hypopycnal flow 234contributes primarily to proximal deposition of supplied fluvial sediment on the shelf, 235whereas hyperpycnal flow predominantly carries sediment to the deep ocean. These 236features indicate that dissolved salt in the ambient water has an important role in 237controlling the fate and transport of sediment on the shelf, and thus shelf formation. 238However, the results also imply that hypopycnal flows themselves rarely induce 239erosion of deposited sediment on the shelf. If we were to continue the simulation for 240a sufficiently long time, the shelf region would eventually be filled with sediment, and 241

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.

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250 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 251formation. This is because hyperpycnal flows contribute less to proximal sediment 252deposition on the shelf surface; this deposition is likely a key factor governing shelf 253extension. The computational conditions of this run are essentially the same as the 254calculation shown above, but some changes are made as follows. First, we extend the 255continental domain length from 15 m to 30 m (so the computational domain is 30 m 256long, but the computational grid size is maintained) and remove the initial shelf from 257the computational domain. This change allows a large accommodation space for 258sediment deposition, and shows whether the model itself generates shelf formation 259and development. Second, we include wave effects on sediment transport 260

(specifically, sediment entrainment from the bed) based on linear wave theory (SI 261Appendix, Methods, Eqs. (S14)-(S19)). The important parameters of this model are 262the significant wave height (H_s) and the wave period (T_w). We set these as $H_s = 0.05$ 263m and $T_{\rm w}$ = 1 s, respectively. These values are quite large for our small, 264laboratory-scale flume, but the erosional force of waves associated with these 265parameters will indeed be shown to be balanced by the sediment supply rate onto 266the shelf. Third, the upstream boundary condition is changed to repeated pulse 267inputs instead of a steady discharge condition, so as to simulate river floods. One 268repeated cycle consists of two time periods: steady water supply with constant 269sediment concentration for a specified period (T_{flood}), and no water or sediment 270supply for another specified period (T_{wave}). Sediment supply (the depositional driver) 271occurs only in period T_{flood}, while the wave effect (the erosional driver) is 272superimposed throughout the entire calculation. In this computational setting, T_{flood} 273characterizes sediment supply during a flood event into the ocean, whereas T_{wave} 274characterizes resuspension of deposited sediment, and redistribution on the shelf 275during multiple dry storm events. In nature, floods and storms can coincide (wet 276storm) or occur separately (dry storm) [e.g., 20]. Here, we set T_{flood} and T_{wave} to be 2771250 s and 20000 s, respectively. We determine the relationship between these time 278scales so as to satisfy a near-bypass condition on the shelf. In other words, in this 279

280 model framework these time scales are imposed by the relationship between the 281 sediment supply rate and wave energy.

The morphodynamics of the shelf generated in this scenario is shown in Fig. 4. 282This figure shows a time series of the bed surface in the run, a feature that helps 283describe stratigraphic architecture. Note that the interval between two lines in the 284figure represents the deposited sediment thickness between four repeated pulse 285inputs. At the early stage of the run, the sediment rainout from the hypopycnal 286plume contributes the proximal sediment deposition on the bottom bed, building up 287the shelf vertically. This shelf development is clearly recognized from the temporal 288change of position of the rollover point. During this stage, the bed surface of the shelf 289is well below the wave base associated with assumed wave energy, so that the 290surface waves play no role in shelf morphodynamics. However, aggradation of the 291shelf surface eventually results in the wave effect becoming significant. Figure 4 292clearly shows that the rollover location starts shifting seaward when the shelf height 293reaches 0.75 m, a point at which waves start to play a role in subaqueous sediment 294transport. When the shelf becomes higher than wave base, the waves can entrain 295sediment deposited on the shelf. The entrained sediment generates a weak 296wave-supported turbidity current. This turbidity current redistributes sediment from 297the shelf region to the slope and rise regions. As a result, the shelf elongates in the 298

seaward direction in the form of a migrating clinoform. Figure 4 suggests that shelf 299morphodynamics at this stage is attributed to the development of a clinoform of 300 permanent form [39]. Figure 5 shows the temporal change in the slope of the slope 301region. The continental slope becomes steeper as the shelf aggrades, but its slope 302asymptotically reaches approximately 4° in the late stage of the simulation. This 303 behavior might be caused by sediment deposition in the rise region (i.e., build-up of 304the basin bottom). Several mechanisms that limit the steepness of the slope such as 305internal waves [45] and submarine groundwater flow [1] are lacking in our model, but, 3064° is nevertheless a reasonable value for continental slopes in nature [1, 46]. 307

Another interesting result of this simulation is the development of sediment 308 waves at the rollover of the modelled continental shelf. This type of morphodynamic 309 feature has been clearly observed in seismic measurements of continental margins 310 [15, 47, 48]. Figure 6 provides a more detailed view of the development of sediment 311waves during three repeated pulse inputs. The sediment waves tend to develop 312below the rollover, where the slope is approximately the steepest value in the 313 simulated continental slope region. These waves migrate slightly to the landward side, 314but also disappear when they reach the shelf. As shown in Fig. 6, the wave effect 315imposed during the entire calculation causes a bottom turbidity current (thin density 316layer). This turbidity current plays an important role in the formation of the sediment 317

waves of Figure 6. The flow features over the sediment waves likely show the 318presence of internal hydraulic jumps, as shown in Figs. 6b, d, and f. This upstream 319 migration of sediment waves bounded by hydraulic jumps induced by a bottom 320turbidity current appears to be another case of deepwater mudwave cyclic steps [49]. 321The disappearance of these waves at the shelf-slope break may be due to the large 322amount of sediment supply from hypopycnal flow, which aggrades the bed and buries 323the waves. This aggradational tendency is much stronger near the distal end of the 324shelf than in the slope region because the slope of the shelf surface is gentler than 325the slope region. These effects cause repeated cycles of formation and disappearance 326of sediment waves near the rollover of the shelf. 327

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.

333

334 **Discussion**

335 The numerical results of this study indicate that a combination of hypopycnal 336 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 337formation of shelf morphology. If one of them is missing, subsequent shelf 338 morphology may be greatly different or even not realized. Hyperpychal flows 339contribute less to proximal sedimentation on the shelf, so that shelf sediment is less 340available for redistributing on the clinoform by wave action than hypopycnal flows. If 341waves are not considered, the shelf height rises to the point that it is exposed, 342eventually resulting in a new coastal plain. However, the physical phenomena 343described in the model are highly simplified. Below, we discuss how these 344simplifications affect the results and interpretation, as well as the implications of the 345numerical results for natural continental shelf formation. 346

The results indicate a purely autogenic mechanism for continental shelf 347formation associated with seaward-migrating clinoforms driven by subaqueous 348 morphodynamic processes. While we do not say that our mechanism is the only one 349 for shelf formation, we emphasize that it needs no allogenic forcing such as sea level 350change. Many previous studies based on sequence stratigraphy have shown that 351allogenic effects of tectonism and sea level variation on continental shelf morphology 352are important, and in some cases they play dominant roles in shelf genesis [3]. The 353formation and development of continental shelves is a long-term process occurring at 354geological timescales. Thus, long-term allogenic effects and short-term autogenic 355

processes can be expected to interact with each other. The autogenic effects analyzed 356in this study thus may be superimposed on allogenic effects, such as the significant 357effect of waves observed in the simulations to plane off the shelf and drive seaward 358clinoform migration. For example, the constant sea level adopted in the simulation 359forces vertical development of the shelf, eventually resulting in seaward clinoform 360 migration without shelf aggradation/degradation [21]. This clinoform development 361likely leads a convex-up trajectory of the rollover point, as shown in Fig. 4. A 362concave-up trajectory of the rollover point is also commonly observed at plate 363margins [e.g., 3]. Sea-level variation changes wave base, so the shelf surface of this 364model should be expected to rise or fall accordingly, as long as sediment supply is 365commensurate to fill accommodation space so created. Sea level rise allows sustained 366 vertical development of the shelf. If waves plays a role in sediment transport at the 367 seafloor during sea level rise, the clinoform will migrate seaward. Vertical 368 development of the shelf with a migrating clinoform (i.e., sigmoid progradation [21]) 369 may result in a concave up trajectory of the rollover. Such allogenic-autogenic 370interactions need to be investigated further in the future; our results, which focus on 371autogenic effects, can help distinguish their relative contributions to the genesis of 372continental shelves [50]. 373

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 375Froude scale similarity, a method which has been effective for engineering-scale 376 models. Although this similarity rule cannot give in truly scale-invariant results for 377turbidity current dynamics, the scale effect on depositional turbidity currents, i.e. the 378weak wave-supported turbidity current associated with hypopycnal flow observed in 379our simulations, may not be very significant [51]. However, it is useful to discuss scale 380effects on other physical phenomena, e.g., the convection instability seen at the 381interface between a surface sediment-laden freshwater plume and salt-rich ambient 382water below. 383

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

386

$$F_{rd} = \frac{U_{inlet}}{\sqrt{\gamma g C_{inlet} H_{inlet}}}$$
(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.

$$\lambda_{\nu} = \lambda_{L}^{1/2}$$
 (2)

An appropriate length scale that characterizes continental shelves is the 400 sustained water depth on the shelf itself; we may be able to determine the geometric 401similarity based on this water depth. In the simulation, the sustained water depth on 402the shelf is approximately 0.2 m, yet this depth in nature is generally around 100 m. 403This gives $\lambda_L = 500$ and $\lambda_v = 22.2$. The length scale of the numerical simulation can be 404upscaled using this geometric similarity. The modeled clinoform relief height is 405 approximately 0.8 m, as shown in Fig. 4, resulting in an upscaled value of 400 m. This 406 is a relatively small-scale clinoform relief for the continental shelf, as seen in the New 407Jersey margin [17], but is still larger than "platform" scale, which is a small-scale shelf 408like morphology generally observed on a continental margin [3, 4]. It is also larger 409 than the Western Adriatic shelf clinoform [15]. The simulated height of the clinoform 410is likely restricted by the initial depth of the basin (i.e., 1.2 m). In addition, the water 411depth seaward of the slope increases in nature, and this has an important effect on 412

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 416 upscaling method, that of Imran et al. [51]. First, the fall velocity in the model, v_{sm} , is 417scaled up by means of kinematic similarity, i.e., $v_{sp} = \lambda_v v_{sm}$. The sediment diameter is 418 then back-calculated using a formula estimating the settling velocity w_f . Here, we use 419the Stokes settling velocity for simplicity. This upscaling gives the following 420relationships. The density flow is characterized as Froude subcritical (F_{rd} =0.82) at the 421inlet, and the inlet Reynolds number, Re, is 3.7x10⁷. The upscaled sediment diameter 422is approximately 0.1 mm, which reasonably corresponds to fine-grained suspended 423sediment. For this size of sediment, settling-driven convection may be dominant 424rather than double-diffusive convection, which is caused by the difference in 425molecular diffusivity between salt and fine sediment, in forming the interfacial 426instability beneath the hypopycnal plume [52] (see details in SI Appendix, Methods). 427The upscaled wave characteristics (i.e., significant wave height of 25 m, and the wave 428period of 22 sec) are somewhat extreme, and could exceed typical storm weather 429conditions. However, the wave characteristics and the two time periods, which 430represent sediment supply and wave-dominated periods (i.e., T_{flood} and T_{wave}), have 431

been chosen to achieve sediment bypass conditions on the shelf. Limited 432computational resources constrain the computational time, so the time scales must 433 be relatively short and the wave characteristics must be extreme in the model. In 434natural environments, the dominant wave height and period are dependent on the 435geographic region and climate, affecting wave base and thus shelf geometry [32]. In 436addition, the return period of the waves considered here also depends on the 437dominant wave intensity, affecting the relation between the timescale of sediment 438supply (depositional driver) and that of the wave-induced sediment redistribution 439(erosional driver). This might be one of the factors causing substantial variation of 440 water depth over the continental shelves on the Earth [5]. Future development of 441computational power will relax the model limitations described above, and will help 442reasonable computational conditions for modeling shelf 443 to set more morphodynamics. 444

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 451present model, it appears that the size of the generated plume and downward 452density flow formed as a result is grid-dependent in the simulation. In addition to this, 453the Reynolds-averaged approach we use here is not able to capture some of 454important physical mechanisms of this phenomenon. For example, the turbulent 455diffusivity modelled in Reynolds-averaged approach is generally larger than the 456molecular diffusivity. The density convection between the surface plume and the 457ambient water in the simulation is mainly driven by settling convection, with the 458double diffusive effect forced to become negligibly small. Such model limitations 459regarding the resolution of fingering is a constraint to field-scale applications of the 460model. This is one reason why we perform our simulations in at small-scale. A 461 submodel that expresses the net sedimentation rate (or net fall velocity) from the 462hypopycnal plume, will be essential for including this effect in large-scale models. A 463 parameter study based on a dataset obtained via DNS [41] can provide useful insight 464in this regard. The importance of double diffusive convection (i.e., salt fingers, [56]) 465was first recognized in stratified thermohaline systems (e.g., Thermohaline Staircases) 466 [57-59]. The problem has been pursued more recently in terms of numerical 467 modeling and experiments in a sediment-salt system [27, 38, 41], so that this effect 468will be included in large-scale models as incorporated in models of thermohaline 469

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 475problem and reduce computational time. Flow and sedimentation patterns may differ 476substantially in a three-dimensional basin. The alongshore dispersal of sediment is an 477important factor for the behavior of positively buoyant, hypopycnal plumes [25]. This 478lateral sediment dispersal of a hypopycnal plume associated with a river mouth (i.e., 479point source) greatly affects the sedimentation rate on the shelf. Neglecting the 480lateral dimension in our simulation may overestimate the sedimentation rate on the 481 shelf. But as Cattaneo et al. [61] have shown in the Adriatic Sea (Figure 4 therein), 482geostropic processes can meld a line of point sources into an effective line source, to 483which this model is applicable. Alongshore sediment dispersal is also important for 484the flow field underneath the hypopycnal plume. For instance, Henniger and Kleiser 485[27] performed large eddy simulations of the dynamics of hypopycnal plumes in a 486small three-dimensional basin. They showed that, because of the limitation of the 487model domain, a backward reverse flow (from seaward to landward) was generated. 488

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

In addition to the flow field, the simulated morphodynamic features of the 491shelf will be affected by the alongshore dimension. Sediment transport to the 492continental slope due to the wave-induced turbidity current migrates the shelf 493clinoform seaward, and develops sediment waves near the rollover. This result 494suggests the formation of a strongly aggradational feature on the modeled 495continental slope. If the alongshore dimension is considered, surface waves may force 496 a more horizontal 2D wave-supported turbidity current rather than a line-type 497current. When such a 2D turbidity current reaches the shelf break, it may migrate the 498clinoform, but there is also a possibility for flow focusing and the formation of 499submarine gullies [43]. Furthermore, as mentioned in the results, a turbidity current 500flowing along a continental slope may also causes the formation of a submarine fan 501system [62]. These different morphodynamic processes are expected to coexist 502during formation of a continental shelf. 503

504

505 **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 515dissolved salt in ambient water on the transport and fate of terrigenous suspended 516sediment. The numerical results clearly show different behaviors between hypo and 517hyperpycnal flows (i.e., with and without dissolved salt in ambient water) on the 518simulated morphodynamics of shelf morphology. Hypopycnal flow shows purely 519depositional features in shelf development. In this flow regime, sediment-laden fresh 520river water overlies salty ambient water in a condition of stable stratification in terms 521of the total density of fluid. However, because of the fall velocity of sediment, an 522interfacial instability develops between the two layers, resulting in significant 523sediment loss from the surface hypopycnal plume. This sediment rainout 524subsequently contributes to the development of a weak turbidity current on the 525bottom. Such a weak current is found to be unable to entrain sediment from the 526

bottom, so that this flow condition contributes purely to proximal deposition of sediment, and the formation of shelf morphology. On the contrary, hyperpychal 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 534amount of sediment supply to the continental shelf. Another factor for continental 535shelf formation is the effect of waves on the redistribution of deposited sediment on 536the shelf. We find that, if a strong surface wave effect is imposed for a time period 537sufficient to flush out sediment deposited by hypopycnal flows down to wave base 538(i.e., to a bypass condition), then continental shelf development with a 539seaward-migrating clinoform can be achieved. Wave energy resuspends sediment 540from the bed, and the subsequent development of a wave-supported turbidity 541current brings sediment from the shelf to the slope, where it deposits below wave 542base. This contributes to seaward migration of the clinoform. Conversely, sediment 543resuspension due to waves restricts further vertical accumulation of sediment on the 544shelf, resulting in a sustained water depth on the shelf associated with the level of 545

546 wave base. These subaqueous hydrodynamic, sediment-transport, and 547 morphodynamic processes lead to continental shelf development with a migrating 548 clinoform, even under conditions of constant sea level.

In nature, autogenic subaqueous factors associated with the morphodynamics 549of continental shelves (internal forces) are superimposed on other allogenic 550processes, such as sea-level variation and tectonism. The relationship between 551autogenic and allogenic effects should be clarified in future work, because sea-level 552variation and tectonism are known to have played important roles in the formation of 553continental shelves [3]. However, in so far as subaqueous processes have received 554less attention in the context of continental-shelf morphodynamics, our results 555provide new insight and interpretations of the genesis of continental shelves. 556

557

558 Methods

The system modeled in this study (i.e., dynamics of hypo- and hyperpycnal 559flows and subsequent morphodynamics of continental shelves) is complex and 560multiscaled in both time and space. It is unreasonable to treat all the physics above in 561a precise way using high-resolution physics-based numerical model at geological time 562scales, so we need several simplifications (see more detail in SI Appendix Methods). 563numerical simulations laboratory-scale, 564Here, we perform at а vertical

two-dimensional field (cross-shore only). The density-driven flow is calculated by an 565unsteady Reynolds-averaged Navier-Stokes model with k- ε type turbulent closure. 566Stratification effects on turbulence production are also considered. The transport 567equation (advection-diffusion equation) is used to calculate the suspended sediment 568transport and dissolved salt in the fluid. Both sediment and salt contribute to the 569density of the fluid, whereas the temperature effect is neglected in our model. The 570sediment is treated as a single-grain cohesionless sediment. To include the effect of 571surface waves on sediment transport, we use a simple linear wave theory. More 572specifically, the additional shear stress due to the presence of a wave boundary layer 573is calculated using a linear wave theory. The details of the model and results are 574described in SI Appendix, and the code and calculation data used in the paper can be 575accessed at the Figshare database [63]. 576

577

578

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758 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 hyperpychal flows of Case 1
 (see *SI Table-S1*) 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 tothe case of Figure 4.

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

repeated pulse inputs.







Elevation (m)





