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A dimensionless framework for predicting submarine fan morphology

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A remarkable diversity exists in the morphology and dynamics of submarine fans, which influence the transport of microplastics, burial of organic carbon, subsea geo-hazards, and their potential to house geofluids and high-resolution paleo-environmental records. Like river deltas, submarine fan morphology is a product of evolving fluid and sediment transport fields, but unlike their terrestrial counterparts we lack a unifying framework to predict their morphology. Here, we simplify critical environmental forcings, like regional slopes and sediment properties, through a dimensionless framework defined by the densimetric Froude number (ratio of inertial to gravitational forces) and Rouse number (ratio of settling velocity of sediments to shear velocity) of turbidity currents. We explore this framework by leveraging a depth-averaged numerical model and measure fan rugosity as a proxy for their morphological complexity. We show a systematic increase in rugosity by either increasing the densimetric Froude number or decreasing the Rouse number of the simulated flows. These

changes reflect observed gradients in the dynamics of channel migration and help discriminate submarine fans that have the potential to impact global climate through sequestration of organic carbon.

Submarine fans form on continental slopes and abyssal plains in deepwater settings and are the ultimate sinks in sediment routing systems. They are crafted by turbidity currents, which arguably move more sediment on Earth than any other transport process and their deposits preserve the thickest accumulations of sediment on Earth¹. Like deltas, the morphologies of submarine fans are quite variable²⁻⁴ and largely result from the dynamics of the channels which move over their surfaces. Unlike deltas, where we have predictive theory for their morphology^{5,6}, we lack a physics-informed theory that successfully predicts the array of observed submarine fan morphologies. This is critical as the surface dynamics that produce these morphologies influence the fidelity of climate change records housed in their strata⁷, the frequency and severity of geohazards that threaten subsea infrastructures such as the network of seafloor cables that hosts the majority of global data traffic^{8,9}, and voluminous geofluid reservoirs¹⁰. We also highlight the importance of flows that traverse submarine fans for global climate as they influence the dispersal of microplastics that impacts ocean carbon sequestration¹¹⁻¹⁴ and the burial and preservation of transported particulate organic carbon^{15,16}.

Turbidity currents are dilute sediment-gravity flows in which the driving gravitational force is supplied by turbulently suspended sediments¹⁷. These currents can travel for 10² hours and up to 10³ kilometers in deepwater settings ($\sim > 4000$ m)^{18,19}, which makes direct monitoring of

modern currents challenging. Further complicating the matter, our ability to infer paleo-hydraulic and sediment-transport regimes from the strata of ancient fans is limited. While physical experiments provided insight into interactions of turbidity currents with an antecedent bed topography²⁰⁻²² over short timescales, we lack experimental methods to produce self-channelized submarine fans constructed by fully turbulent flows that transport most of their sediment in suspension.

We overcome the direct observational and experimental limitations that prevent us from linking properties of turbidity current to the morphology of submarine fans by leveraging a physics-based and parallel numerical model. This model simulates the interactions of a depth-averaged turbidity current (Fig. 1a) with a uniform and non-erodible antecedent surface (Fig. 1b). We investigate the hypothesis that submarine fan shape is largely controlled by regional bathymetric slopes and the properties of sediments (size and cohesion) delivered to submarine fans. We achieve this by solving continuity equations²³ for fluid mass, sediment mass, momentum, and turbulent kinetic energy for turbidity currents: in addition to erosion and deposition of cohesive sediments²⁴ and flocculation of mud particles^{25,26}. A steady current enters through an inlet channel into a square domain that is scaled by the advection length of the mean grain size in suspension. In this manner, our models simulate currents that rapidly lose confinement downslope of a canyon or channel-to-fan transition. To isolate the influence of flow hydraulics and sediment transport capacity on submarine fan shape and dynamics we neglect subsidence and changing

climatic forcings (i.e. sea-level, water flux, and sediment supply) within model runs. Simulations are stopped after a defined volume of sediment is released into the model domain.

The dimensionless regime

Classification systems exist for submarine fans based on characteristics of the terrestrial feeder system²⁷, preserved grain sizes^{28,29}, facies associations³⁰⁻³², and preserved morphology^{33,34}. These classification schemes leverage observations that fans on high slopes (e.g. Squamish fan) are generally small (< 10's of km) and sandy^{3,35}, intermediate slope fans (e.g. Gulf of Cadiz) contain both sand and mud⁴, and fans that form on low slopes (e.g. Zaire fan) are large (> 1000 km) and rich in mud content^{2,36}. While the studies that underpin these classification systems report correlations for parameters that influence fan shape, they generally carry tremendous scatter, which limits their predictive power. Many of these classification systems assume links to the hydraulics and sediment-transport capacity of turbidity currents, but we lack theory that explicitly links fan shape to flow processes.

We propose a dimensionless regime (Fig. 2) where submarine fan dynamics and resulting morphology are defined by two dimensionless variables, the densimetric Froude number (Fr_D) and Rouse number (Ro) that weigh competing forces in turbidity currents. The Fr_D quantifies the ratio of inertial to gravitational forces within a flow, while the Ro describes the ratio of settling velocity of sediments to shear velocity in the flow. To explore this regime, we solve for an equilibrium slope, which we set as our initial bathymetric gradient, from a choice of Fr_D as function of bed friction

and clear water entrainment³⁷. We compute for mean grain sizes in suspension at the inlet from a choice of Ro as a function of their settling velocity. While Fr_D and Ro are free to change over the evolving fan surface, we classify fans based on their inlet Fr_D and Ro values. To capture a wide range of morphodynamic behaviors, we explore ranges in Fr_D and Ro for a depth-averaged turbidity current (Table 1). To avoid either highly erosional or depositional flows, we performed sensitivity analyses that guided the range of conditions explored.

End member morphodynamics

The submarine fans in our regime diagram have morphologies and surface dynamics that are defined by Fr_D and Ro and display striking similarity to their field counterparts. Here we focus on a comparison of fans constructed by subcritical ($Fr_D < 1$) flows with low Ro values to supercritical ($Fr_D > 1$) flows with high Ro values.

Our model captures both large and small-scale geomorphic features of subcritical and low Ro fans that are preserved on low slopes (e.g., Zaire^{2,36,38}) (Fig. 3a). We observe multiple sinuous channels bound by prominent levees. These fans are crafted by channel networks that fluctuate between one-to-many active channels. The channels generate a distributive pattern by avulsing at a variety of distances from the inlet channel. On the levees, flow tends to locally change criticality and induce formation of cyclical steps. We observe a hierarchy of bifurcations with genetically related mouth bar deposits that help partition flux of sediment and water moving through the growing distributive network. This partitioning is variable and leads to the formation of

asymmetric branching channels. In these fans, sand is mainly transported in channels, while silts and muds are deposited on levees, lobes, and distal parts of the outer fan.

Supercritical and high Ro fans are characterized by a single low-sinuosity channel (Fig. 3b). At the channel-mouth bar transition the flow undergoes a hydraulic jump, where the increased flow height and loss of turbulence lead to deposition of sediments in the form of cyclical steps³⁹. These cyclical bedforms (Fig. 3b) migrate upstream in the channel until the flow confinement decreases and an avulsion is triggered. This type of fan is predominantly sandy because flow shear stresses inhibit deposition of silt and mud. The absence of flux partitioning at the channel-mouth bar transition and avulsions triggered in a single channel system that visit many locations through time induces an overall radial fan shape.

Submarine fan shape and texture

The shape of submarine fans and the size of the particles they house provide insight into the hydraulics and sediment transport capacity of the flows that constructed them. Here we focus on the planform complexity of submarine fans and use regional bathymetric slopes (or slope estimates for paleo-fans) and deposit grain sizes to constrain the Fr_D and Ro responsible for constructing a given fan. First, we quantify the rugosity of submarine fans as a proxy for the complexity of their morphologies. Contrary to deltas, where the shoreline represents an important contour for delta front deposition⁶, there is no established contour that reflects the influence of forcing conditions on submarine fan shape. We overcome this by utilizing a deposit thickness contour that delineates

116 the depositional midpoint in submarine fans. Specifically, we use a mass-balance transformation⁴⁰,
 117 which measures downstream distance in terms of sediment mass lost to deposition in a basin. We
 118 define a dimensionless mass extraction parameter, χ , as:

$$\chi(r) = \frac{1}{V_{s,b}} \int_0^L B(r) H_s(r) dr$$

119 Where $V_{s,b}$ is the total volume of sediment stored in the basin, L is the total downstream length of
 120 a basin, B is the basin width at a radial distance measured from the end of the entrance channel r ,
 121 and H_s is the average thickness of preserved strata along a strike transect defined by r . The value of
 122 χ ranges between 0 and 1, for instance, a value of 0.5 implies that half of the sediment stored in a
 123 basin is upstream of that location. We compute for a semicircle with an origin at the end of the
 124 inlet channel and a radius equivalent to $\chi = 0.5$. We contour the fan based on the mean deposit
 125 thickness on this semi-circle and evaluate its rugosity as,

$$126 \quad R(\chi = 0.5) = \frac{1}{N} \sum_{i=1}^n \frac{|r_c - r_{mid}|}{r_{mid}}$$

127 where N is the number of deposit thickness maps, n is number of x-y locations on the semicircle,
 128 r_c is the radial distance between the origin of the semicircle and an x-y location on the mean
 129 thickness contour, and r_{mid} is the radius of the $\chi = 0.5$ semicircle (Fig. 4a). We exclude models that
 130 exhibit near complete sediment bypass.

131 The simulations show a systematic increase in planform roughness, quantified through
 132 rugosity, as one explores from the low Fr_D and high Ro corner of the regime diagram towards the

high Fr_D and low Ro domain (Fig. 4b). We interpret the joint influence of Fr_D and Ro on fan rugosity as thus. Given fans of constant Fr_D , decreasing Ro results in longer transport distances for particles in suspension, allowing active and relatively stable channels to quickly prograde. In addition, decreasing Ro leads to more poorly sorted sediments, due to our inlet suspension criteria (see methods). Like prior research on deltaic channels⁶, we propose that an increase in sorting promotes more frequent and asymmetric channel bifurcations, leading to multiple active channels. While this increase in active channels facilitates the delivery of sediment to more fan locations, the stable and asymmetric nature of these channels results in jagged contours with high rugosity values.

Traversing our regime along paths of constant Ro but increasing Fr_D corresponds to higher shear velocities (Fig. 5, extended) for flows of equivalent thickness at the inlet, which inhibits deposition of silts and finer sands and promotes the maintenance of fewer active channels. These channels terminate in a single large mouth bar deposit covered with backstepping cyclical bedforms. This promotes channel mobility through infrequent avulsions caused by the loss of confinement due to the backstepping bedforms. As a result, fan rugosity increases due to the elongation of the relatively active few channels, contrary to the processes responsible for increasing rugosity through decreasing Ro . However, as Fr_D increases past criticality sediment bypass conditions are reached and further increases in Fr_D produce unfavorable conditions for channel initiation and maintenance.

While rugosity alone is not a unique indicator of Fr_D and Ro , fan rugosity coupled with knowledge of one of these parameters allows for the estimation of the other. For example, the rugosity of modern submarine fans can be estimated with high resolution bathymetric and shallow seismic surveys, whereas for ancient fan deposits it can be estimated with industry-grade 3-D seismic surveys. Fr_D can then be estimated with the regional (paleo)slopes and existing empirical functions for drag coefficients and clear water entrainment³⁷, as implemented in our model. Fan rugosity and Fr_D can then be used to invert for the Ro of the inlet flow to a fan. Furthermore, sediment sizes suspended in the inlet flow can be estimated from knowledge of the feeder channel depth. This would involve estimating the shear velocity of the inlet flow from channel depth and Fr_D , followed by use of the Ro to solve for sediment sizes in transport through a settling velocity.

Alternatively, estimates of flow Ro in a fan feeder channel coupled with fan rugosity allows for the inversion of Fr_D . Here, the challenge is to estimate a paleo-flow Ro of the feeder channel. This can be done with access to statistics of deposit grain sizes, for example from core measurements. This would entail using an assumption that the largest preserved particles met a Shield's criterion, which could be used to invert for a shear velocity. The Ro can then be calculated with a characteristic settling velocity of the median particle size in transport. To accomplish this, we found and utilized an empirical relationship (see methods) between fan rugosity and a ratio formed by the sizes of the median particles in transport to the median size in the deposit (Fig. 6).

Results from our dimensionless regime diagram have implications beyond the morphology of submarine fans. We highlight our results that suggest flows traversing high slope submarine fans

are efficient at transporting fine sediments that can include microplastics. As a result, microplastics could preferentially bypass these fans and get diffused into the deep oceans. Deep water currents can further redistribute microplastics along with terrigenous sourced nutrients, which severely impacts the ability of phytoplankton to fix CO₂ via photosynthesis¹³. Microplastics ingested by these phytoplankton can also negatively impact marine food-webs and the rate of particulate carbon production and preservation¹²⁻¹⁴.

On the contrary, modern fans on low slopes often have complex morphologies, suggesting they were constructed by low Fr_D and Ro flows. Our regime diagram indicates that these fans efficiently trap mud supplied by turbidity currents. A high fraction of sediment in the mud size range (< 62.5 μm) consists of clays whose mineral surface properties⁴¹ favors adsorption of particulate organic carbon, which can be preserved if rapidly buried to only several cms of depth. This suggest that subcritical fans on low slope settings can impact global climate by sequestering large volumes of carbon.

Methods

In the interest of capturing a range of morphodynamic behaviors within submarine fans that are defined by different slopes and mean grain sizes, we propose a dimensionless regime space. This is achieved by defining the horizontal axis of the regime space as Fr_D , which quantifies the ratio of inertial to gravitational forces within a turbidity current. It is calculated as $Fr_D = u/\sqrt{Rgh}$, using depth-average values for important forcing variables within the flow, such as velocity (u), concentration (c), and height of the current (h). We set $c = 5\%$, $h = 5\text{ m}$, $R = 1.65$, and $g = 9.8\text{ m/s}^2$ at the inlet, and therefore, by varying Fr_D we only vary the velocity magnitude at the inlet. We compute for an equilibrium slope⁴⁴ $S = ((e_w + cd) * Fr_D^2 + 0.5 * e_w)$, as a function of friction at the bed and clear water entrainment from a choice of Fr_D , where e_w is the clear water entrainment coefficient, calculated from the Fr_D ³⁷, and cd is the coefficient of friction with a fixed value of 0.004. On the vertical axis, we define the $Ro = w_s/(k * u_*)$, which quantifies the ratio of settling velocity of sediments (w_s) to shear velocity (u_*) in the flow, where k is von Karmen's constant. We compute the mean settling velocity of sediments $\langle w_s \rangle$ from a choice of Ro using the Dietrich⁴² method, which then allows us to indirectly compute for the grain sizes in suspension (Fig. 5a extended). We compute a lognormal distribution sampled by 10 quartz sediment sizes with a 5 μm clay particles (10% of the total sediment concentration) added to the final sediment mixture. We compute sorting (Fig. 5b extended) for this log normal distribution by leveraging the shields curve of suspension, such that D_{99} or finer sediment sizes will honor the Bagnold Criterion¹⁷. We

209 conducted sensitivity analyses on the dimensional variables that defines Fr_D and Ro . In these
210 models, we found similar absolute values for fan rugosity in experiments with different
211 dimensional scales, but equivalent dimensionless scales. Next, we performed sensitivity analyses
212 to examine how the percent of the total sediment concentration comprised of clay particles
213 influences the absolute magnitude of resulting morphology metrics. We find that relative to
214 models documented here, which utilized a mud fraction of 10%, changing mud content between
215 over a range of 5-60% did change the placement of channels and lobe, but only changed the
216 absolute values of fan rugosity by at most 17%. As such, a third axis defined by mud content could
217 be generated for our regime diagram to account for erosion and deposition dynamics imparted by
218 the cohesive fraction of the sediment concentration. However, this third axis is likely less
219 significant for fan rugosity than the axes defined by Fr_D and Ro .

220 We scale the simulation domain size by leveraging a modified version of the advection
221 length, $la = \langle u \rangle * h_c / w_s$, which describes the minimum horizontal distance over which the
222 mean grain size within a flow can be transported before making contact with the bed⁴³. In this
223 formulation, $\langle u \rangle$ is the depth-average velocity of the flow at the inlet, h_c describes the height of
224 the center of mass within a turbidity current. This height is calculated as, $h_c = h * (0.5 * z_c + 0.25(1 - z_c))$, where h is the height of the current at the inlet, and z_c is the
225 normalized distance from the bed to the maximum volumetric concentration in the flow, and is
226 set to 0.9 when $Fr_D < 0.5$ and $z_c = 0.09 * Fr_D^{-2.8}$ when $Fr_D > 0.5$ ⁴⁴.

The evolution of topography is solved on a flat non-erodible surface with a triangular irregular network (TIN) grid of average 50 m mesh. For post-processing we interpolate the data onto a Cartesian grid. The entrance channel and upstream boundary walls are closed (and reflect flows), whereas the side and downstream boundaries are open and allow flows to exit the domain. We implement a model stopping condition by fixing the total volume of sediment released into the domain at 2.5×10^{07} cubic meters. As a result, subcritical cases require longer computation run-time due to relatively low velocity magnitudes, whereas supercritical simulations take relatively shorter times, given the rapid delivery of the set amount of total sediment volume.

The simulator uses a four equation model²³ that solves for bedload fluxes⁴⁵, erosion rates⁴⁶, deposition rates⁴⁷, flocculation of clay particles^{25,26}, and the influence of cohesion on the underlying deposit²⁴. Models are run with a dynamic time step that is a function of grid spacing, flow velocity, and wave speed.

Our method to invert for fan forming flow Fr_D from Ro and fan rugosity takes advantage of deposit grain size statistics. We highlight a gradient in our regime diagram of a ratio between median particle sizes in transport to the median particle sizes preserved in the fan, GS_{Ratio} . This gradient is in the same direction as the observed gradient in fan rugosity as a function of Fr_D and Ro . An empirical relationship was then fit to allow for estimation of GS_{Ratio} from fan rugosity (Fig. 6 extended).

References

- 1 Talling, P. J. *et al.* Key Future Directions For Research On Turbidity Currents And Their Deposits. *Journal of Sedimentary Research* **85**, 153-169 (2015).
- 2 Babonneau, N., Savoye, B., Cremer, M. & Klein, B. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. *Marine and Petroleum Geology* **19**, 445-467 (2002).
- 3 Sweet, M. L. *et al.* Sediment routing from shelf to basin floor in the Quaternary Golo System of Eastern Corsica, France, western Mediterranean Sea. *Bulletin* **132**, 1217-1234 (2020).
- 4 Habgood, E. L. *et al.* Deep-water sediment wave fields, bottom current sand channels and gravity flow channel-lobe systems: Gulf of Cadiz, NE Atlantic. *Sedimentology* **50**, 483-510 (2003).
- 5 Nienhuis, J. *et al.* Global-scale human impact on delta morphology has led to net land area gain. *Nature* **577**, 514-518 (2020).
- 6 Caldwell, R. L. & Edmonds, D. A. The effects of sediment properties on deltaic processes and morphologies: A numerical modeling study. *Journal of Geophysical Research: Earth Surface* **119**, 961-982 (2014).
- 7 Hessler, A. M. & Fildani, A. Deep-sea fans: tapping into Earth's changing landscapes. *Journal of Sedimentary Research* **89**, 1171-1179 (2019).

266 8 Heezen, B. C. & Ewing, W. M. Turbidity currents and submarine slumps, and the 1929
267 Grand Banks [Newfoundland] earthquake. *American journal of Science* **250**, 849-873
268 (1952).

269 9 Carter, L., Gavey, R., TALLING, P. J. & Liu, J. T. Insights into submarine geohazards from
270 breaks in subsea telecommunication cables. *Oceanography* **27**, 58-67 (2014).

271 10 Weimer, P. & Pettingill, H. S. Global overview of deep-water exploration and production.
272 (2007).

273 11 Kane, I. A. *et al.* Seafloor microplastic hotspots controlled by deep-sea circulation. *Science*
274 **368**, 1140-1145 (2020).

275 12 Wright, S. L., Thompson, R. C. & Galloway, T. S. The physical impacts of microplastics on
276 marine organisms: a review. *Environmental pollution* **178**, 483-492 (2013).

277 13 Shen, M. *et al.* Can microplastics pose a threat to ocean carbon sequestration? *Marine*
278 *pollution bulletin* **150**, 110712 (2020).

279 14 Cole, M. *et al.* Microplastics alter the properties and sinking rates of zooplankton faecal
280 pellets. *Environmental science & technology* **50**, 3239-3246 (2016).

281 15 Galy, V. *et al.* Efficient organic carbon burial in the Bengal fan sustained by the Himalayan
282 erosional system. *Nature* **450**, 407-410 (2007).

283 16 Hage, S. *et al.* Efficient preservation of young terrestrial organic carbon in sandy turbidity-
284 current deposits. *Geology* **48**, 882-887 (2020).

285 17 Bagnold, R. A. Auto-suspension of transported sediment; turbidity currents. *Proceedings*
286 *of the Royal Society of London. Series A. Mathematical and Physical Sciences* **265**, 315-319
287 (1962).

288 18 Azpiroz-Zabala, M. *et al.* Newly recognized turbidity current structure can explain
289 prolonged flushing of submarine canyons. *Science advances* **3**, e1700200 (2017).

290 19 Pirmez, C. & Imran, J. Reconstruction of turbidity currents in Amazon Channel. *Marine*
291 *and petroleum geology* **20**, 823-849 (2003).

292 20 Imran, J., Parker, G. & Harff, P. Experiments on incipient channelization of submarine
293 fans. *Journal of Hydraulic Research* **40**, 21-32 (2002).

294 21 Parsons, J. D. *et al.* A preliminary experimental study of turbidite fan deposits. *Journal of*
295 *Sedimentary Research* **72**, 619-628 (2002).

296 22 Straub, K. M. & Mohrig, D. Quantifying the morphology and growth of levees in aggrading
297 submarine channels. *Journal of Geophysical Research: Earth Surface* **113** (2008).

298 23 Parker, G., Fukushima, Y. & Pantin, H. M. Self-accelerating turbidity currents. *Journal of*
299 *Fluid Mechanics* **171**, 145-181 (1986).

300 24 Winterwerp, J. C. & Van Kesteren, W. G. *Introduction to the physics of cohesive sediment*
301 *dynamics in the marine environment.* (Elsevier, 2004).

302 25 Kuprenas, R., Tran, D. & Strom, K. A shear-limited flocculation model for dynamically
303 predicting average floc size. *Journal of Geophysical Research: Oceans* **123**, 6736-6752
304 (2018).

305 26 Winterwerp, J. C. A simple model for turbulence induced flocculation of cohesive
306 sediment. *Journal of hydraulic research* **36**, 309-326 (1998).

307 27 Clark, J., Kenyon, N. & Pickering, K. Quantitative analysis of the geometry of submarine
308 channels: implications for the classification of submarine fans. *Geology* **20**, 633-636 (1992).

309 28 Richards, M., Bowman, M. & Reading, H. Submarine-fan systems I: characterization and
310 stratigraphic prediction. *Marine and Petroleum Geology* **15**, 689-717 (1998).

311 29 Stow, D. A. & Mayall, M. Deep-water sedimentary systems: new models for the 21st
312 century. *Marine and Petroleum Geology* **17**, 125-135 (2000).

313 30 Bouma, A. H. Sedimentology of some flysch deposits. *Agraphic approach to facies*
314 *interpretation* **168** (1962).

315 31 Lowe, D. R. Sediment gravity flows; II, Depositional models with special reference to the
316 deposits of high-density turbidity currents. *Journal of sedimentary research* **52**, 279-297
317 (1982).

318 32 Mutti, E. & Ricci Lucchi, F. Turbidites of the northern Apennines: introduction to facies
319 analysis. *International geology review* **20**, 125-166 (1978).

320 33 Vail, P. The stratigraphic signatures of tectonics, eustacy and sedimentology-an overview.
321 *Cycles and events in stratigraphy*, 617-659 (1991).

322 34 Shanmugam, G. Glossary: A supplement to “Submarine fans: A critical retrospective
323 (1950–2015)” in the Journal of Palaeogeography (2016, 5 [2]). *Journal of Palaeogeography*
324 **5**, 258-277 (2016).

325 35 Cornard, P. H. & Pickering, K. T. Supercritical-flow deposits and their distribution in a
326 submarine channel system, middle Eocene, Ainsa Basin, Spanish Pyrenees. *Journal of*
327 *Sedimentary Research* **89**, 576-597 (2019).

328 36 Picot, M., Droz, L., Marsset, T., Dennielou, B. & Bez, M. Controls on turbidite
329 sedimentation: insights from a quantitative approach of submarine channel and lobe
330 architecture (Late Quaternary Congo Fan). *Marine and Petroleum Geology* **72**, 423-446
331 (2016).

332 37 Parker, G., Garcia, M., Fukushima, Y. & Yu, W. Experiments on turbidity currents over an
333 erodible bed. *Journal of Hydraulic Research* **25**, 123-147 (1987).

334 38 Deptuck, M. E. & Sylvester, Z. in *Submarine geomorphology* 273-299 (Springer, 2018).

335 39 Hamilton, P. B., Strom, K. B. & Hoyal, D. C. Hydraulic and sediment transport properties
336 of autogenic avulsion cycles on submarine fans with supercritical distributaries. *Journal of*
337 *Geophysical Research: Earth Surface* **120**, 1369-1389 (2015).

338 40 Strong, N., Sheets, B., Hickson, T. & Paola, C. in *Fluvial sedimentology VII* Vol. 35 243-
339 253 (International Association of Sedimentologists Special Publication 35, 2005).

340 41 Mayer, L. M. Surface area control of organic carbon accumulation in continental shelf
341 sediments. *Geochimica et Cosmochimica Acta* **58**, 1271-1284 (1994).

342 42 Dietrich, W. E. Settling velocity of natural particles. *Water resources research* **18**, 1615-
343 1626 (1982).

- 43 Ganti, V., Lamb, M. P. & McElroy, B. Quantitative bounds on morphodynamics and
implications for reading the sedimentary record. *Nature communications* 5, 1-7 (2014).
- 44 Sequeiros, O. E. Estimating turbidity current conditions from channel morphology: A
Froude number approach. *Journal of Geophysical Research: Oceans* 117 (2012).
- 45 Meyer-Peter, E. & Müller, R. in *IAHSR 2nd meeting, Stockholm, appendix 2.* (IAHR).
- 46 Garcia, M. & Parker, G. Entrainment of bed sediment into suspension. *Journal of Hydraulic
Engineering* 117, 414-435 (1991).
- 47 Garcia, M. H. Depositional turbidity currents laden with poorly sorted sediment. *Journal
of hydraulic engineering* 120, 1240-1263 (1994).
- 48 Vendettuoli, D. *et al.* Daily bathymetric surveys document how stratigraphy is built and its
extreme incompleteness in submarine channels. *Earth and Planetary Science Letters* 515,
231-247 (2019).

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Author contributions

The authors contributed to this manuscript as follows, D.C.H, K.M.S, M.S and A.W conceived of this study and developed the theoretical framework; A.W carried out the numerical work with assistance and guidance from M.S; A.W processed and interpreted the data; D.C.H, M.S, and K.M.S reviewed the interpretations; A.W and K.M.S wrote the manuscript with feedback from D.C.H and M.S.

Competing Interests

The authors declare no competing interests.

Additional Information

Extended data for this paper is available at [To be decided]

Correspondence and requests for materials should be addressed to A.W.

Data availability

Data will be made available as per *Nature Geoscience* guidelines.

380

381 **Fig.1 | Numerical setup. a**, Schematic cross-section of a turbidity current with important depth-
 382 averaged terms highlighted in red. **b**, Example of a model domain with a flat non-erodible slope.
 383 Red lines trace upstream boundaries of domain that are closed and reflect flow, whereas black lines
 384 trace boundaries that are open and allow the flow to exit the domain. The black arrow represents
 385 the debouchment of flow from the inlet channel and dominant flow direction.

Case ID	Fr_D^1 [1/1]	Ro^2 [1/1]	Slope degree	U^3 [m/s]	u_*^4 [m/s]	$D50^5$ [um]	$Dmax^6$ [um]	Sorting [1/1]	Ws^7 [m/s]	8 Duration [hour]
1	0.46	0.032	0.001	0.9	0.06	24	463	1.8	0.002	30210
3	0.63	0.032	0.002	1.3	0.08	25	645	2.0	0.003	22088
6	1.00	0.032	0.008	2.0	0.13	23	1178	2.4	0.004	13809
7	1.17	0.032	0.013	2.4	0.15	22	1497	2.6	0.005	11807
9	1.60	0.032	0.036	3.2	0.20	17	2632	3.1	0.007	8633
31	0.46	0.101	0.001	0.9	0.06	83	463	1.1	0.006	30210
33	0.63	0.101	0.002	1.3	0.08	94	645	1.2	0.008	22088
36	1.00	0.101	0.008	2.0	0.13	109	1178	1.5	0.013	13809
37	1.17	0.101	0.013	2.4	0.15	113	1497	1.6	0.015	11807
39	1.60	0.101	0.036	3.2	0.20	114	2632	1.9	0.021	8633
51	0.46	0.148	0.001	0.9	0.06	115	463	0.9	0.009	30210
53	0.63	0.148	0.002	1.3	0.08	135	645	1.0	0.012	22088
56	1.00	0.148	0.008	2.0	0.13	165	1178	1.2	0.019	13809
57	1.17	0.148	0.013	2.4	0.15	175	1497	1.3	0.022	11807
59	1.60	0.148	0.036	3.2	0.20	188	2632	1.6	0.030	8633
71	0.46	0.194	0.001	0.9	0.06	145	463	0.7	0.011	30210
73	0.63	0.194	0.002	1.3	0.08	172	645	0.8	0.015	22088
76	1.00	0.194	0.008	2.0	0.13	219	1178	1.0	0.025	13809
77	1.17	0.194	0.013	2.4	0.15	235	1497	1.1	0.029	11807
79	1.60	0.194	0.036	3.2	0.20	265	2632	1.4	0.039	8633
91	0.46	0.240	0.001	0.9	0.06	173	463	0.6	0.014	30210
93	0.63	0.240	0.002	1.3	0.08	207	645	0.7	0.019	22088
96	1.00	0.240	0.008	2.0	0.13	270	1178	0.9	0.031	13809
97	1.17	0.240	0.013	2.4	0.15	294	1497	1.0	0.036	11807
99	1.60	0.240	0.036	3.2	0.20	341	2632	1.3	0.049	8633

¹ Densimetric Froude Number ; ² Rouse Number ; ³ Mean velocity at the inlet; ⁴ Mean shear velocity at the inlet ; ⁵ Mean sand diameter

⁶ Maximum sand diameter ; ⁷ Mean settling velocity of suspended material at the inlet ; ⁸ Total simulation time on a super computer

Table 1. | Select model variables used in this study.

Fig.2 | Dimensionless regime diagram. A subset of simulated fans displays different planform morphologies that result from defined combinations of Fr_D and Ro . Note that range of fan thicknesses displayed in color and the horizontal scale vary between models. Models in the first row have domain size of 55 x 50 km whereas the remaining models have a domain size of 35 x 30 km. White bar denotes 5 km of length. Additional variables are listed in Table 1.

Fig.3 | Comparison of endmember model behavior to field analogs. a, Deposit thickness (m), velocity (m/s), Fr_D state, and grain sizes (um) in the subcritical simulation (40 x 35 km) indicate; a distributive transport pattern, multiple active and sinuous channels, a hierarchy of bifurcations, and overall mud rich deposit that resembles aspects of the Zaire fan³⁸ (left panel). **b,** Supercritical fan simulation (35 x 30 km) shows characteristic cyclical bedforms formed due to a hydraulic jump, a single active and low-sinuosity channel, and sand rich deposit that resembles a high slope modern fan⁴⁸ (Left panel). White color bar is 5 km. See movies for these runs in supplemental materials.

Fig.4 | Planform morphometry in simulated fans. a, Deposit thickness maps show contour used to measure rugosity. The black semicircle defines a distance from the inlet at which half of the sediment is stored in the model domain. The red contour is computed for a mean elevation along the black semicircle. b, Matrix shows computed rugosity for all models. White area represents models in which input sediment largely bypassed model domains. Colored dots correspond to rugosity measurements for fans displayed in Fig. 4a.

Extended figures

Fig.5 | Parameter design for the proposed dimensionless regime. a, Mean grain sizes, b. Sorting, c. Maximum grain size, d. Inlet shear velocity.

Fig.6 | Empirical relationship between grain size ratio and fan rugosity. **a**, Matrix shows grain size ratio ($G_{s_{ratio}}$) computed for all models with significant deposit. This ratio is defined by median grain sizes in suspension at the inlet to the median grain sizes preserved in model domains. **b**, A logarithmic trend is fit to the scatter plot of $G_{s_{ratio}}$ and fan rugosity. This trend line allows for estimation of mean grain sizes in suspension for a given Fr_D and Ro value.

Supplementary Files

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- [Subcritical.avi](#)