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A dimensionless framework for predicting submarine fan morphology

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Limited observations of active turbidity currents at field scales challenges the development of theory that links flow dynamics to the morphology of submarine fans. Here we offer a framework for predicting submarine fan morphologies by simplifying critical environmental forcings such as regional slopes and properties of sediments, through densimetric Froude (ratio of inertial to gravitational forces) and Rouse numbers (ratio of settling velocity of sediments to shear velocity) of turbidity currents. We leverage a depth-average process-based numerical model to simulate an array of submarine fans and measure 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 turbidity currents. These trends reflect gradients in the dynamics of channel migration on the fan surface and help discriminate submarine fans that effectively sequester organic carbon rich mud in deep ocean strata.

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. In the last few decades, research has focused on the influence submarine fans have on global climate. Two avenues along this path are the management of marine litter, including the transport of microplastics into deep oceans¹¹⁻¹⁵, and burial of particulate organic carbon^{16,17}.

Turbidity currents are dilute sediment-gravity flows in which the driving gravitational force is supplied by turbulently suspended sediments¹⁸. These currents can travel for 10² hours and up to 10³ kilometers in deepwater settings (bathymetry ~> 4000 m)^{19,20}, 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 topography²¹⁻²³ over short timescales, we still lack experimental methods that can produce self-formed channels by fully turbulent flows and which display sufficient mobility to form a fully dynamic fan surface^{24,25}.

These challenges have influenced the development of forward numerical models of turbidity currents and their resulting submarine fans. Large computational costs associated with some models developed in the early part of this century, which required computation of complex and fully turbulent turbidity currents defined by Navier-Stokes equations, motivated initial efforts to adapt simplified and reduced complexity process-based models²⁶⁻²⁸. While these modeling efforts generate realistic gross scale compensational stacking patterns and lobe-scale geometries over an antecedent surface, they did not account for erosion of the underlying deposits. The lack of spatial and temporal variations in deposition and erosion on the fan surface limited their applicability to unchannelized and purely depositional submarine fans.

We overcome the direct observational, experimental, and modeling limitations that prevent us from linking properties of turbidity currents to the complex morphologies of submarine fans by leveraging a previously developed, parallel process-based numerical model called EMstrata^{29,30}. This model is based on the depth-average approximation of flow parameters in 3D Navier-Stokes equations of fully turbulent flows³¹. The model solves continuity equations for fluid mass, sediment mass, linear momentum, and turbulent kinetic energy for turbidity currents: in addition to erosion and deposition of cohesive sediments³² and flocculation of mud particles^{33,34} (see methods). As such we are able to successfully simulate self-formed channels on fan surfaces that are laterally mobile and avulse through time to generate complex submarine fan morphologies. Here, we posit that submarine fan morphology is largely controlled by the densimetric Froude ($Fr_D = \frac{U}{\sqrt{Rcgh}}$; where U is the down system current velocity, R is the submerged specific density of sediment, c is volumetric sediment concentration, g is gravitational acceleration, and h is the current

thickness) and Rouse ($Ro = \frac{w_s}{ku_*}$; where w_s is the sediment fall velocity, k = von Kármán's constant, and u_* is the flow shear velocity) numbers of turbidity currents. More specifically, we hypothesize that flows with low Fr_D and Ro numbers transport most of their sediment in suspension through a growing network of branching channels and generate distributive fan morphologies. Whereas flows with high Fr_D and high Ro numbers transport sediment in both suspension and bedload through networks that are often defined by a single channel that avulses over time to generate a radial fan morphology.

We initiate simulations by introducing a depth-averaged turbidity current which traverses an inlet channel into a square domain that is scaled by the advection length of the median grain size in suspension (Fig. 1). In this manner, we 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.

Results

The dimensionless regime

Classification systems exist for submarine fans based on characteristics of the terrestrial feeder system³⁵, preserved grain sizes^{36,37}, facies associations³⁸⁻⁴⁰, and preserved morphology^{41,42}. Other studies leverage observations that fans on high slopes (e.g. Squamish and Golo fan) are generally small (< 10's of km) and sandy^{3,43}, intermediate slope fans (e.g. Gulf of Cadiz and East Breaks) contain both sand and mud^{4,44}, and fans that form on low

slopes (e.g. Zaire fan) are large (> 1000 km) and rich in mud content^{2,45}. 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 currently lack a predictive framework that explicitly links fan shape to flow processes.

We propose a dimensionless regime where submarine fan dynamics and resulting morphology are defined by two dimensionless variables, the densimetric Froude (Fr_D) and Rouse number (Ro) that weigh competing forces in turbidity currents (Fig. 2). 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 implement 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 entrainment⁴⁶. We compute for median grain sizes in suspension at the inlet from a choice of Ro as a function of their settling velocity. While Fr_D and Ro dynamically 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, extended). To avoid either highly erosional or depositional flows, we performed sensitivity analyses that guided the range of conditions explored.

End member morphodynamics

The simulated submarine fans in our regime diagram have morphologies and surface dynamics that are defined by Fr_D and Ro and display striking similarity to both modern and

preserved examples of submarine fans (Fig. 3-5). In this section, we focus on endmember submarine fans that are crafted by turbidity currents characterized by subcritical ($Fr_D < 1$), transcritical ($Fr_D = 1$) and supercritical ($Fr_D > 1$) flow and defined sediment-transport conditions through Ro . Each numerical submarine defined by the aforementioned conditions is then compared to a field counterpart.

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^{2,45,47}) (Fig. 3a). We observe multiple self-formed sinuous channels bound by prominent levees (Fig. 3b-c). 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 (Fig. 3b-c). On the levees, flow tends to locally change criticality and induce formation of cyclical steps (Fig. 3d). We observe a hierarchy of bifurcations that help partition flux of sediment and water moving through the growing distributive network (Fig. 3b-c). 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 (Fig. 3e).

Transcritical and intermediate Ro submarine fan surfaces (e.g. Gulf of Cadiz and East Breaks)^{4,44} are characterized by self-formed low sinuosity channels that extend in the primary flow direction (Fig. 4a-c). The channels are bound by well-formed levees that help maintain the bypass conditions for the majority of their simulated time (Fig. 4d). The channel avulses infrequently after increased aggradation rates within the channel causes a decrease in flow confinement. The newly formed channels extend in the major flow direction, which

eventually leads to an ellipsoidal fan morphology. In this type of fan, sand is transported in the channels and deposited on lobes and proximal levees, whereas silt and mud are deposited on the distal parts of the fan surface (Fig. 4e).

Supercritical and high Ro submarine fans (e.g. Squamish fan)^{3,43} are characterized by a self-formed single low-sinuosity channel (Fig. a-b). At the channel-lobe 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 steps⁴⁸ (Fig. 5b-d). These cyclical bedforms 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 (Fig. 5e). The absence of flux partitioning at the channel-lobe transition and avulsions triggered in a single channel system that visits 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 (Fig. 6a). 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 the depositional

midpoint in submarine fans. Specifically, we use a mass-balance transformation⁴⁹, which measures downstream distance in terms of sediment mass lost to deposition in a basin. We define a dimensionless mass extraction parameter, χ , as:

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

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

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

where N is the number of deposit thickness maps, n is number of x-y locations on the semicircle, r_c is the radial distance between the origin of the semicircle and an x-y location on the mean thickness contour, and r_{mid} is the radius of the $\chi = 0.5$ semicircle (Fig. 6a). We exclude models that exhibit near complete sediment bypass.

The simulations show a systematic increase in planform roughness, quantified through 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. 6b). 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 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.

Surface and subsurface predictions

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 entrainment⁴⁶, 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. 7a-b).

Discussion

Defining conditions that lead to the diversity of submarine fan morphologies found on the ocean floor opens the potential for inversion of fan form for paleo-environmental reconstructions and prediction of their future role in the global carbon cycle. We link the complexity of submarine fan form to critical dimensionless parameters that are proxies for the gradients of continental margins and the particle sizes in transport. However, we note

these *dimensionless* variables are constructed with important *dimensional* parameters (e.g. current thickness, mean velocity, and diameter of particles in transport). Further, we note that many large fan systems, including the Zaire^{2,45}, Indus⁵⁰, and Bengal fans¹⁶, are found on low gradient margins and house fine-grained deposits. In contrast, many steep margin and sandy systems are also small in scale^{3,43,51}. This dimensional correlation between fan size, margin gradient and preserved deposit texture might point to important contributions from the dimensional parameters housed in the Fr_D and Ro . To test the importance of scale on our results, namely the dimensionless regime, we ran sensitivity tests in which a suite of fans were generated (Fig. 8 a-c, extended). These runs had different combinations of input flow thickness (Fig. 8 b, extended), velocity (Fig. 8 c, extended), and particle sizes, but shared equivalent Fr_D and Ro . The results of these tests support our hypothesis that submarine fan complexity is set by the Fr_D and Ro of the turbidity currents that formed them. While gradient and particle sizes delivered to a fan are correlated to a fan's size, the complexity of its shape is set by flow and sediment-transport fields. Specifically, Fr_D influences the morphology of a submarine fan by setting thresholds in erosion and deposition in combination with a choice of Ro . A component of the correlation between fan size, gradient, and particle sizes can also be explained from our dimensionless parameters. For example, a flow that is characterized by low Fr_D and Ro generates a fan surface that is large in scale due to increased advection lengths of the median grain sizes in suspension, compared to a fan that is formed by flows that have a higher Fr_D and Ro . We show this scale difference in the simulated fans of our regime diagram (Fig. 2, subcritical fans ($Fr_D < 1$) reach up to 40 kms of downstream length as compared to some supercritical fans ($Fr_D > 1$) that are less than 10 km in downstream length).

We further explore the role of cohesive sediment on fan shape through a suite of sensitivity tests. This is motivated by studies of other depositional forms, for example deltas, where sediment cohesion has been linked to the rugosity of shorelines^{6,52}. We investigate this by varying the input mud content in the flow and examine how the percent of the total sediment concentration comprised of clay particles influences the absolute magnitude of the resulting morphology metrics (Fig. 9, extended). We find that while changing mud content over a range of 5-60% of the input flux did change the specific placement of channels and lobes, it only produced modest changes in fan rugosity (at most 17% from our base case models). As such, a third axis defined by mud content could be generated for the regime diagram implemented here to account for erosion and deposition dynamics imparted by the cohesive fraction of the sediment concentration. However, this third axis is likely less significant for fan rugosity than the axes defined by Fr_D and Ro .

For turbidity currents to propagate any significant distance, they must generate enough turbulence to enable suspension of sediments, referred to as the Knapp-Bagnold criterion^{18,53} ($U > W_s/S$). We avoid failure of this criterion and thus excessive depositional flows at the inlet by enforcing a Shield's criterion that requires suspension of the D_{99} of the sediment distribution. This leads to emerging trends in sorting as a function of Fr_D and Ro at the inlet (Fig. 10, extended). We find that sorting influences the fraction of a fan surface covered by active channels and the style and rate of channel mobility. Submarine fans constructed by low Fr_D and Ro , coupled with poor sediment sorting, show a higher degree of channelization and development of distributary networks. The development of these complex networks can be linked to the wide range of settling velocities for the particles in transport, which leads to spatially variable deposition and erosion rates. This generates

multiple nucleation sites for channel initiation and the formation of mouth bars that drive channel bifurcation (Fig. 3c). We note that both degree of channelization and the distributary nature of the emergent channels decreases when Fr_D and Ro increase, as flows become well sorted. In these fans, the incoming flows rapidly become purely depositional, suppressing the growth of complex channel patterns. We note that at extremely high Fr_D values channelization is lost as most sediment bypasses the domain, hindering levee development that confines flows (Fig. 2). Future investigation could explore different criteria to define input grain size distributions, for example, keeping sorting constant across a spectrum of Fr_D and Ro , which may possibly quantify further the influence of sorting on emergent patterns of channel networks on the fan surface.

Deepwater submarine fans are the ultimate sink in routing systems and their complex morphologies have been described through a hierarchy of landforms⁵⁴, which can be linked to a hierarchy of features preserved in their strata^{55,56}. Further, recent work suggests that differences in migration rates of features across hierarchical levels controls the degree to which scales of stratigraphic features (i.e. preserved channel body thickness) resemble common scales of surface features (i.e. channel depth)⁵⁷. This complex stratigraphic hierarchy can develop even under constant environmental forcing, as we show with our model, due to intricate feedback mechanisms between flow and antecedent bed surfaces (autogenics). These autogenic processes and their stratigraphic products makes restoration of signals of paleo-environmental significance challenging^{58,59}. The model leveraged in this study produces intricate autogenic behavior and a hierarchy of landforms on the fan surface, all with different migration rates, which vary as a function of Fr_D and Ro of turbidity currents (See movies, extended). For instance, we show that low gradient fans with relatively low Ro

promotes a distributive network of channels that delivers sediments to many locations on the surface of a fan. The complexity of these networks is not constant over a model run and varies as channels avulse and new channels evolve with different initial conditions. As such, networks can vary in number of active distributaries anywhere between one to many. This intricate and rather dynamic style of autogenic behavior challenges stratigraphers' ability to decipher signals of environmental significance from preserved fan strata, such as from outcrops and seismic volumes. We also show that high gradient fans crafted by high Fr_D tend to localize deposition in and at the terminus of a single channel network. This style of deposition at the channel-to-lobe transition facilitates choked flow conditions and triggers an avulsion, which results in a shift of locus of deposition on the fan surface. This autogenic configuration reduces the area on the fan surface that is active at any one time. The lack of compensational stacking over these meso-timescales likely imparts significant hiatuses in the fan strata, reducing the temporal completeness of preserved records. The flows that craft these single channel networks also efficiently bypass clay particles that carry sedimentary signals⁷. Combined, periods of depositional stasis on the fan surface and bypass of fines likely limits our ability to leverage high gradient strata for paleo-climatic inversions. The observed complexity in the migration dynamics of channels that emerges as a function of Fr_D and Ro also likely limits our ability to leverage some reduced complexity models for deciphering signals of climatic and tectonic significance from ordered submarine fan strata. This is due to the limited range of autogenic processes currently produced by some models, which often do not contain rules to describe threshold changes in autogenic processes as a function of flow and sediment-transport conditions²⁸, as we highlighted in this study.

Results from our dimensionless regime diagram have implications beyond predicting the morphology of submarine fans and the inversion of fan form for paleo-environmental conditions. We show that submarine fans crafted by turbidity currents that are traversing relatively low gradients and transporting fine particles in suspension can efficiently trap more mud compared to fans crafted by turbidity currents traversing higher gradients with relatively coarse particles in suspension (Fig. 11, extended). We highlight that flows with subcritical Fr_D and low Ro favors higher settling rates for sediment that are less than 62.5 μm in diameter, due to the relatively low shear velocities that characterizes these systems. A high fraction of sediment in the mud size range ($< 62.5 \mu m$) consists of clays whose mineral surface properties⁶⁰ 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 slopes in deepwater settings are favorable spots for sequestering large volumes of organic carbon via increased burial rates of mud supplied by turbidity currents. The higher trapping potential and preservation rates of organic carbon in these fans¹⁶ likely buffers long term atmospheric CO_2 levels and can significantly impact global climate change on geological timescales.

We conclude that the remarkable diversity of submarine fan morphology on the modern ocean floor can be generated solely by changing critical dimensionless variables that describe the flow and sediment-transport fields of turbidity currents. This unifying framework ties transport processes to fan form and is defined by the Fr_D and Ro of turbidity currents. Our results demonstrate the utility of leveraging a process-based forward model, which accounts for all important turbidity current forcing mechanisms, for simulation of complex and geologically realistic submarine fan morphology. Finally, the controls on fan

complexity, highlighted in our regime space, will aid inversion of fan form for paleo-
environmental conditions and help identify those fans that act as critical reservoirs in Earth's
carbon cycle.

Methods

Flow-forcing and sediment-transport parameters. 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 $Fr_D = u/\sqrt{Rgch}$, 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 slope $S = ((e_w + cd) * Fr_D^2 + 0.5 * e_w)$, 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 ⁴⁶, 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 Kármán's constant.

Input grain size distribution and criterion for suspension. We compute the mean settling velocity of sediments $\langle w_s \rangle$ from a choice of Ro using the Dietrich⁶¹ method, which then allows us to indirectly compute for the grain sizes in suspension (Fig.10a extended). We compute a lognormal distribution sampled by 10 quartz sediment sizes with 5 μm clay particles (10% of the total sediment concentration) added to the final sediment mixture. We compute sorting (Fig. 10b 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 Criterion¹⁸.

Scaling of the simulation domain. We scale the simulation domain by leveraging a modified version of the advection length, $la = \langle u \rangle * h_c / w_s$, which describes the minimum horizontal distance over which the mean grain size within a flow can be transported before making contact with the bed⁶². In this formulation, $\langle u \rangle$ is the depth-average velocity of the flow at the inlet, h_c describes the height of 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 normalized distance from the bed to the maximum volumetric concentration in the flow, and is set to 0.9 when $Fr_D < 0.5$ and $z_c = 0.09 * Fr_D^{-2.8}$ when $Fr_D > 0.5$ ⁶³.

Boundary conditions. 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 1.25×10^{11} 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.

Simulator. EMstrata uses a four equation model³¹ that solves for bedload fluxes⁶⁴, erosion rates⁶⁵, deposition rates⁶⁶, flocculation of clay particles^{33,34}, and the influence of cohesion on

the underlying deposit³². Models are solved using a finite volume method with a dynamic time step that is a function of grid spacing, flow velocity, and wave speed. A more detailed description of the depth-averaged theory, governing equations and analyses of their approximate analytical solutions, and a choice of the numerical solver is published in prior studies^{29,30}.

Inversion to median grain sizes in transport. 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. 7).

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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]

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Data availability

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

Figures

Fig.1 | Numerical setup. **a**, Schematic cross-section of a turbidity current with important depth-averaged terms highlighted in red. **b**, Example of a model domain [50 x 50 km] with a flat non-erodible slope. Black lines trace upstream boundaries of domain that are closed and reflect flow, whereas blue lines trace boundaries that are open and allow the flow to exit the domain.

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 last row have domain size of 55 x 50 km whereas the remaining models have a domain size of 35 x 30 km. White bars denotes 10 km of length. Additional variables are listed in Table 1.

Fig.3 | Comparison of a simulated subcritical fan to the Zaire fan system, offshore Congo. **a**, Bathymetry map of the modern Zaire fan system⁴⁷. **b**, Deposit thickness (m). **c**, Velocity field on the active fan surface. **d**, Fr_D state on the active fan surface. **e**, Grain sizes on the active fan surface. The subcritical fan simulation is characterized by a distributive transport pattern, multiple active and sinuous channels, a hierarchy of bifurcations, and overall mud rich deposit that resembles the Zaire fan⁴⁷ (**a**). [Reprinted by permission from Springer Nature, Springer Geology, Submarine Fans and Their Channels, Leveed, and Lobes, Mark E. Deptuck, Zoltan Sylvester, 2018]. See movie for this model run in supplemental materials.

Transcritical fan ($Fr_D = 1$)

a) RGB blended horizon stack
EastBreaks

Fig.4 | Comparison of a simulated transcritical fan to the Quaternary East Breaks basin-IV submarine fan, offshore Gulf of Mexico. a, spectrally decomposed seismic horizon of the East Breaks basin-IV submarine fan. The yellow dotted lines highlight channelized bodies that prograded into basin-IV. **b**, Deposit thickness (m). **c**, Velocity field on the active fan surface. **d**, Fr_D state on the active fan surface. **e**, Grain sizes on the active fan surface. The supercritical fan simulation (**b-e**) shows a sinuous channel that progrades into the basin (**b-c**), formation of cyclical steps on the active lobe surface (**b**), and distribution of grain sizes on the active fan surface (**e**). See movie for this model run in supplemental materials.

Supercritical fan ($Fr_D > 1$)

Fig.5 | Comparison of a simulated supercritical fan to the modern Squamish fan, offshore British Columbia. a, Bathymetry map of the modern Squamish fan⁵¹. **b,** Deposit thickness (m). **c,** velocity field on the active fan surface. **d,** Fr_D state on the active fan surface. **e,** Grain sizes on the active fan surface. The supercritical fan simulation (**b-e**) shows characteristic cyclical bedforms (**a**) formed due to hydraulic jumps, a single active and low-sinuosity channel (**c**), and sand rich deposit (**e**) that resembles a high slope modern fan⁵¹ (**a**). See movie for this model run in supplemental materials.

Fig.6| Planform morphometry in simulated fans. **a**, Deposit thickness maps for select submarine fans show contour used to measure rugosity. The white semicircle defines a distance from the inlet upstream of which half of the sediments in the model domain are stored. The black contour is computed for a mean elevation along the semicircle. Color bars denote thickness [m]. **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. 6a.

Fig.7 | Empirical relationship between ratio of median grain size in transport at the inlet to median grain size preserved in the deposit and fan rugosity. a, Matrix shows grain size ratio (Gs_ratio) computed for all models with a significant deposit. **b,** A logarithmic trend is fit to the scatter plot of Gs_ratio and fan rugosity. This trend line allows for estimation of mean grain sizes in suspension for a given Fr_D and Ro value.

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

Fig.8| Sensitivity of submarine fan shape to dimensional scales in Froude number (Fr_D) of the flow at the inlet. **a**, Simulated submarine fans in this row display our base case scenario where at the inlet we fix the height of the current (h) and volumetric concentration of suspended sediments (c). So by varying Froude number of the flow we only vary the mean velocity (u) at the inlet. **b**, In this row, we show the resulting submarine fan morphology by doubling the height of the current (h) and reducing the concentration (c) by half to keep equivalent dimensionless value for Fr_D . **c**, In this row, we increase the mean velocity (U) of the current at the inlet by proportionally increasing the height of the current (h) and concentration of suspended sediments (c). We show that while the internal architecture of the simulated strata changes as a result of the variation in the dimensional scales, the overall shape remains similar and shows strong dependence to unique dimensionless values of Fr_D and Ro of turbidity current at the inlet. All models have identical grid dimensions and color bars denote thickness [m].

Fig.9| Sensitivity of submarine shape to ranges in mud content. Matrix shows the influence of cohesion on the resulting fan morphology by increasing input mud content from 5 to 60% at the inlet for a subset fans from the regime diagram. Note the final morphology in these models might be different i.e. placement of channels and lobes on the fan surface, however the overall shape remains similar. Color bar denotes the thickness of the fan at the end of the simulation.

Fig.10| Select parameters design for the dimensionless regime. a, Median grain sizes, b. Sorting, c. Maximum grain size, d. Inlet shear velocity.

Fig.11| Preservation of mud across the dimensionless regime. Matrix shows preservation of total mud content in all simulated submarine fans. The white region denotes models that are predominantly sandy and did not deposit any significant mud content.

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