GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G51385.1

Manuscript received 16 May 2023
Revised manuscript received 30 August 2023
Manuscript accepted 15 September 2023

Published online 27 September 2023

Controls on upstream-migrating bed forms in sandy submarine channels

Rebecca G. Englert[1,2,*], Age J. Vellinga[3,4], Matthieu J.B. Cartigny[2], Michael A. Clare[4], Joris T. Eggenhuisen[5], and Stephen M. Hubbard[1]

[1]Department of Earth, Energy, and Environment, University of Calgary, Calgary, Alberta T2N 1N4, Canada
[2]Department of Geography, Durham University, Durham DH1 3LE, UK
[3]School of Earth & Ocean Science, University of Southampton, Southampton SO14 3ZH, UK
[4]Ocean BioGeosciences, National Oceanography Centre, Southampton SO14 3ZH, UK
[5]Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, Netherlands

ABSTRACT

Submarine channels parallel river channels in their ability to transport sediment. However, in contrast to rivers, sediment transport and bed-form development in submarine channels are less well understood. Many steep (>1°), sandy submarine channels are dominated by upstream-migrating bed forms. The flow conditions required to form these upstream-migrating bed forms remain debated because the interactions between turbidity currents and active bed forms are difficult to measure directly. Consequently, we used a depth-resolved numerical model to test the role of flow parameters that are hypothesized to control the formation of upstream-migrating bed forms in submarine channels. While our modeling results confirmed the importance of previously identified flow parameters (e.g., densiometric Froude number), we found that basal sediment concentration in turbidity currents is the strongest predictor of upstream-migrating bed-form formation. Our model shows how locally steep gradients enable high sediment concentrations (average >5 vol%) in the basal parts of flows, which allow the development of cyclic step instabilities and their associated bed forms. This new insight explains the previously puzzling observation that upstream-migrating bed forms are abundant in proximal, steep, sandy reaches of submarine channels, while their occurrence becomes more intermittent downslope.

INTRODUCTION

Turbidity currents, particularly those that carve submarine channels, are one of the most effective processes for delivering sediment, carbon, nutrients, and plastics to the deep sea (Shepard and Dill, 1966). Along their paths, these flows form a wide variety of bed forms within and outside of submarine channels that vary in size, morphology, and composition (Normark et al., 1979; Wynn and Stow, 2002). Here, we focused on bed forms found in sandy submarine channels that are tens of meters in wavelength (small sediment waves; sensu Symons et al., 2016), develop on steep slopes (>1°), and migrate upstream (Hughes Clarke et al., 2014). Trains of upstream-migrating bed forms are commonly observed in the proximal reaches of submarine channels or canyons, where they are typically located downslope of even steeper (>10°), bed-form-free stretches of seafloor such as Gilbert-type deltas or head-wall gullies (Fig. 1). These bed forms become less frequent distally on lower-gradient channel reaches, where they often appear in association with higher-gradient knickpoints (Paull et al., 2011; Chen et al., 2021). Despite their important role in facilitating sediment transport, controls on the formation and distribution of bed forms in submarine channels remain uncertain (Paull et al., 2010; Talling et al., 2015).

To date, insights into the dynamics of upstream-migrating bed forms by river flows and, to a lesser extent, by turbidity currents have been established from numerical models and laboratory experiments (e.g., Alexander et al., 2001; Kostic and Parker, 2006; Covault et al., 2017). Bed forms in these studies are associated with either in-phase surface waves (antidunes; Gilbert, 1914) or trains of hydraulic jumps (cyclic steps; Parker, 1996). Initiation of upstream-migrating bed forms has been linked to flow supercriticality (Froude number >1), sediment transport regime (erosion), and slope breaks (Kostic, 2011; Balmforth and Vakil, 2012; Cartigny et al., 2014; Fedele et al., 2016; Ohata et al., 2017). In addition, it has been suggested that density stratification is important for bed-form development by turbidity currents (Postma and Cartigny, 2014; Tilston et al., 2015). The influence of density stratification in the formation of sandy, upstream-migrating bed forms in submarine channels has remained untested because turbidity current stratification has yet to be included in numerical models and is hard to quantify near the seafloor due to high sediment concentrations that restrict the placement and penetration of monitoring equipment (Talling et al., 2015). Depth-resolved computational fluid dynamics (CFD) models enable full-scale simulations that incorporate density stratification and are thus a logical next step to investigate the formation of upstream-migrating bed forms by turbidity currents.

Here, we used a depth-resolved CFD model to (1) constrain the flow properties that control the formation of decameter-scale upstream-migrating bed forms by turbidity currents flowing down steep, sandy slopes, and (2) provide an explanation for the intermittent occurrence of these bed forms in modern submarine channels.

METHODS

Fifteen trials were conducted using a Reynolds-averaging Navier-Stokes model (FLOW-3D®). This model has been used previously to simulate turbidity currents with sediment concentrations up to 27 vol% (Basani et al., 2014;

Rebecca G. Englert https://orcid.org/0000-0003-3051-593X
*rebecca.englert@ucalgary.ca

CITATION: Englert, R.G., et al., 2023, Controls on upstream-migrating bed forms in sandy submarine channels: Geology, v. XX, p. , https://doi.org/10.1130/G51385.1

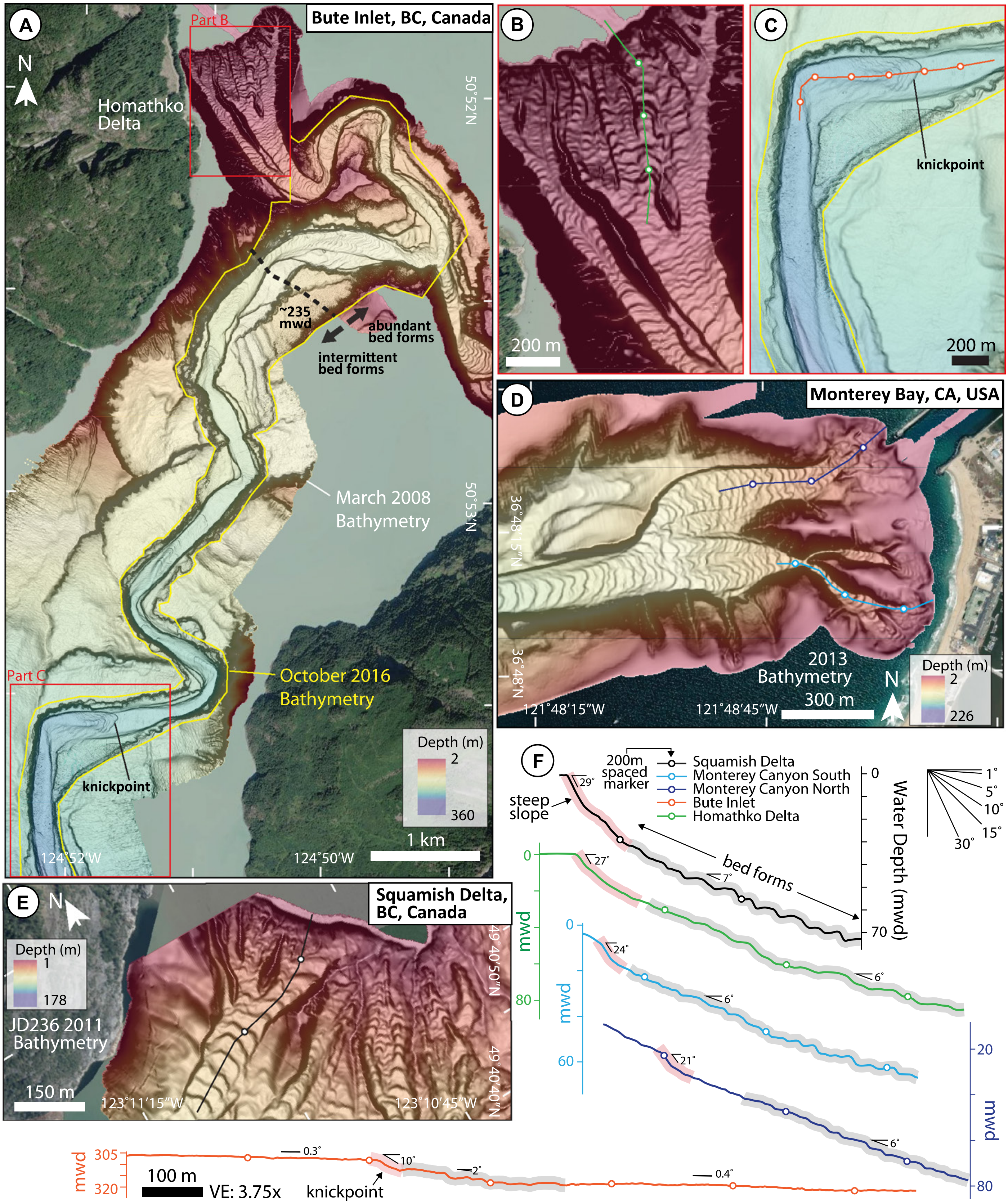

Figure 1. Decameter-scale upstream-migrating bed forms in submarine channels. (A–E) Bathymetric maps showing bed-form distribution in: (A–C) Bute Inlet, British Columbia (BC), where bed forms occur on Homathko Delta (B), proximal channel, and just downstream of knickpoints (C), (D) proximal Monterey Canyon, where bed forms are abundant and start in steep gullies close to shelf edge, and (E) Squamish Delta, where bed forms extend up to steep, smooth Gilbert-type delta. (F) Bathymetric profiles for each example. Positions of profiles are shown in parts A–E. Circles are 200 m spaced horizontal markers on both graphs and maps. Segments containing bed forms correspond to areas of undulations on profiles and crescentic trains on maps. VE—vertical exaggeration; mwd—water depth in meters.

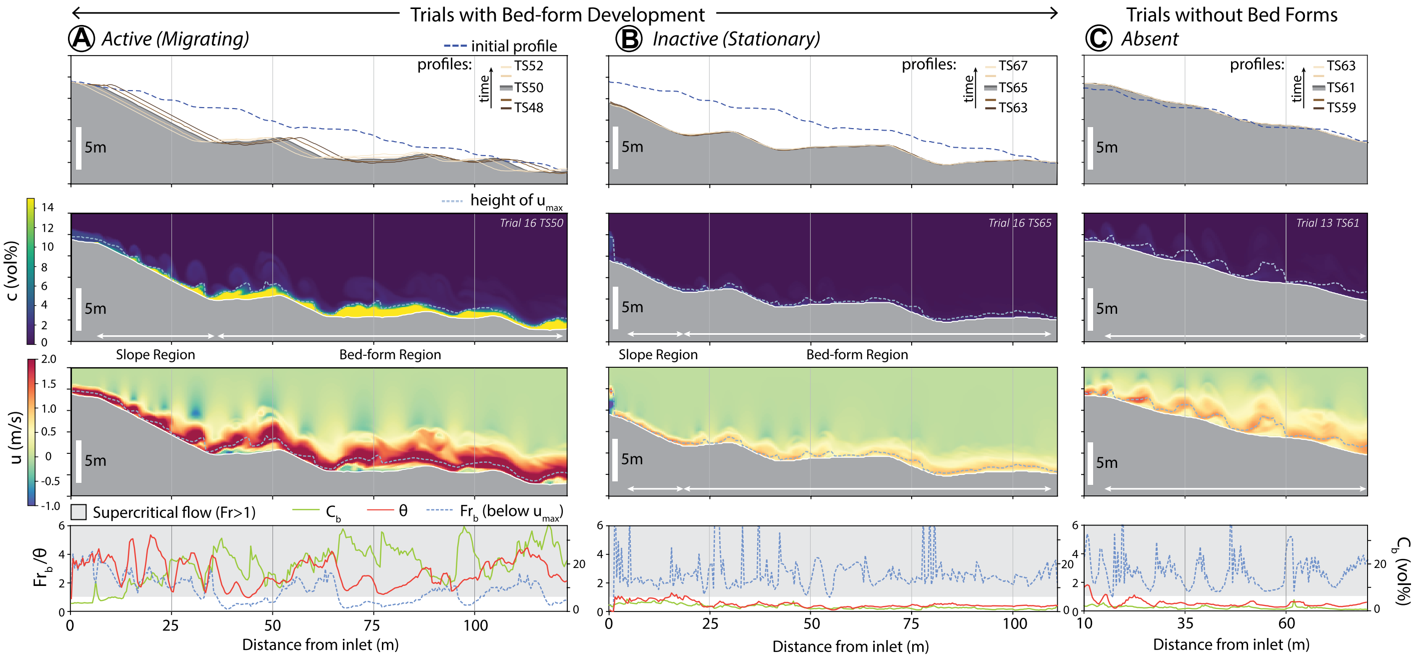

Figure 2. Snapshots of flow properties and bed topography for each flow state over specified portion of horizontal domain: (A) active, (B) inactive, and (C) absent. Bed topography panels (top row) show bed evolution over five time steps (TS) or 200 s. Initial profile is indicated by blue dashed line. Data output from model for one time step is shown in sediment concentration (c) (second row) and velocity (*u*) (third row) panels. These were used to calculate additional parameters shown below (using formulas in Appendix S2 in the Supplemental Material [see text footnote 1]). Densiometric Froude numbers were calculated from vertically averaged parameters for base of flow (Fr_b) below velocity maximum and show where flow is supercritical (Fr >1) and subcritical (Fr <1) (fourth row). Shields numbers (θ) indicate where there is higher shear stress on bed and greater sediment mobility (fourth row). White arrows denote regions that were used to analyze flow properties shown in Figure 3.

Maselli et al., 2021) and upstream-migrating bed forms in river flows (Vellinga et al., 2018). The model includes a fixed inlet grain-size distribution (D_{50} = 150 μm); bed-load transport (Meyer-Peter and Müller, 1948); suspended load transport; turbulence-induced sediment diffusion; sediment entrainment (Mastbergen and Van Den Berg, 2003); hindered sediment settling; no turbulence modification by sediment; and no grain-to-grain interactions. The model was two-dimensional, consisting of a 30-m by 200-m grid with 0.1-m vertical and 0.4-m horizontal resolution. Flows were simulated for 1–2 h over an inclined erodible bed with meter-scale random rugosity to accelerate bed-form initiation. The inlet conditions for the turbidity currents were altered for each trial: flow thickness (0.5–2 m), flow velocity (0.5–1.7 m/s), sediment concentration (C = 1–3.8 vol%), and slope (2.7°–6.1°; for details, see Appendix S1 in the Supplemental Material[1]).

We analyzed flow properties (Froude supercriticality, erosion, and/or stratification) that had been previously proposed to control the formation of upstream-migrating bed forms. Depth-averaged densiometric Froude numbers were calculated for the basal portion of the flow below the velocity maximum (de Cala et al., 2020). Shields numbers were calculated to characterize grain mobility (Appendix S2).

RESULTS

Three flow states (active, inactive, and absent) were identified based on the coupled evolution of the flow and the sediment bed topography (Fig. 2). In six simulation trials, flows quickly reworked the initial slope and formed a concave slope break that preceded a train of bed forms downslope. The bed forms migrated upslope and were 20–60 m long and 0.5–2.5 m high. Trials with upstream-migrating bed-form development could be divided into two flow states: (1) an active state, where flows displayed a consistent configuration with an upstream-migrating bed-form train (Fig. 2A); and (2) an inactive state, where flows did not modify the pre-established bed-form topography, and the bed forms remained stationary (Fig. 2B; Appendix S3). Flows were typically in an active state at the beginning of trials. Toward the end of the trials, erosion beneath the flow inlet led to strongly waning flow conditions and a transition to an inactive state over the bed forms (Fig. 2B; Appendix S4). In the remaining nine simulation trials, no bed forms appeared, and the flows gradually smoothed the initial slope profile through minor erosion and deposition (Fig. 2C; Appendix S3). These trials without upstream-migrating bed forms made up the third flow state—absent.

Flow properties were considered over different horizontal segments (white arrows in Fig. 2). In trials with bed forms, they were compiled over: (1) a slope region defined as the steep segment upslope of the slope break, and (2) a subsequent bed form–containing region (Fig. 2). Inactive flow states were only considered when bed topography was still characterized by bed forms formed during the previous active flow state (Appendix S4). Trials without bed forms were analyzed over a region of the slope away from the flow inlet (Fig. 2).

A comparison of flow states showed that bed-form–forming flows (active flow state) were always denser and faster than flows that did not form or interact with bed forms (absent and inactive flow states; Fig. 3A). We then explored the flow parameters hypothesized to control the formation of upstream-migrating bed forms.

Froude Supercriticality

All flows were dominantly Froude supercritical, with median densiometric Froude numbers (Fr_{50}) > 1 (Fig. 3B). Densiometric Froude numbers for flows in an active state were overall lower and included values below 1 over bed forms (Figs. 2A and 3B; Appendix S2). Tran-

[1]Supplemental Material. Appendices S1–S4: Additional information on the boundary conditions, flow evolution, and flow state delineation in simulation trials. Appendix S3 is made up of 14 mp4 files. Please visit https://doi.org/10.1130/GEOL.S.24168582 to access the supplemental material, and contact editing@geosociety.org with any questions.

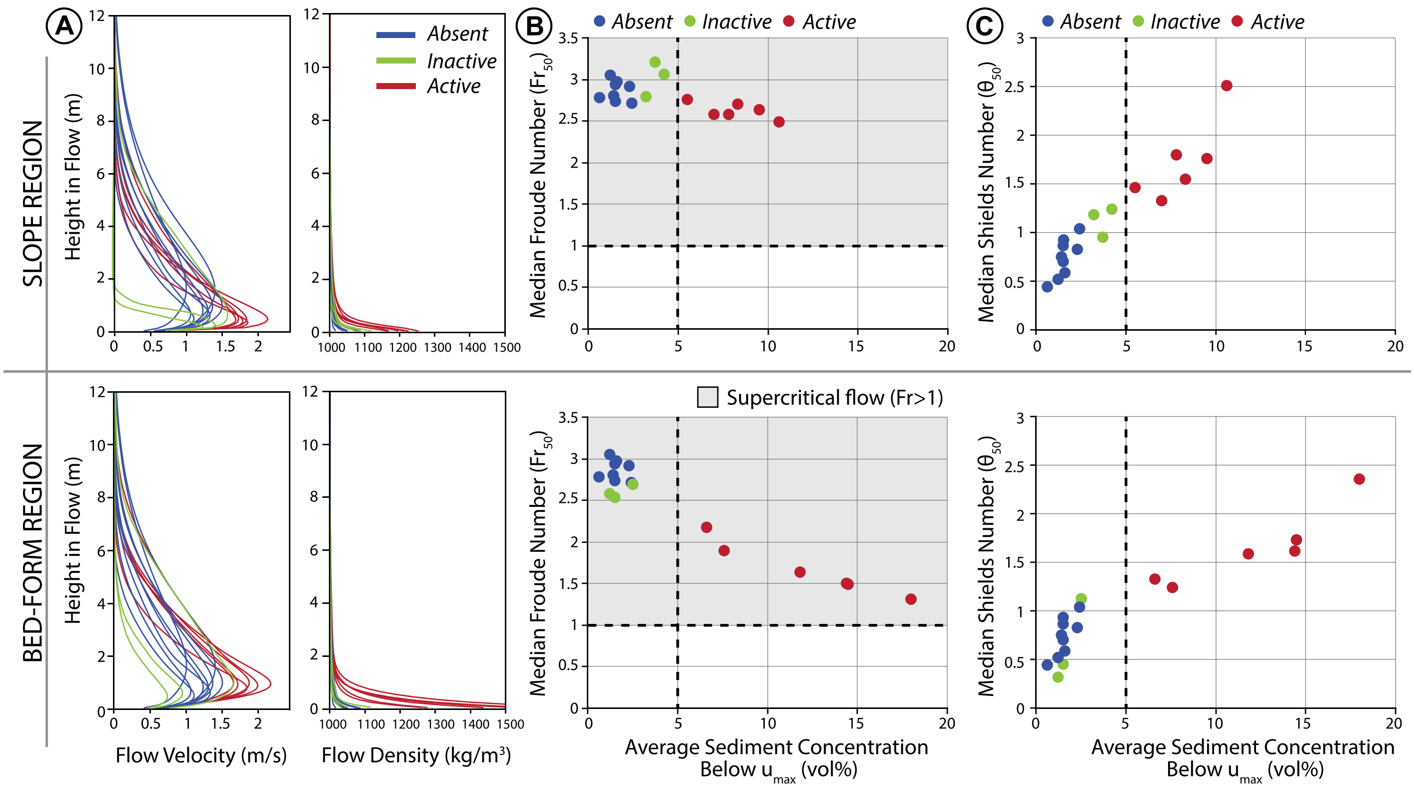

Figure 3. Comparison of flow properties between absent flow state to slope and bed-form regions of active and inactive flow states, including: (A) average density and velocity profiles; (B) average sediment concentration and median (Fr_{50}) densiometric Froude number in basal portion of flow; and (C) average sediment concentration in basal portion of flow and median (θ_{50}) Shields number.

sitions to subcritical flow conditions (Fr <1) occurred in bed-form troughs, where the flow abruptly thickened and indicated the presence of hydraulic jumps associated with the upstream-migrating bed forms (Fig. 2A).

Flow Stratification

All flows were turbulent and characterized by density profiles that were vertically stratified (Fig. 3A; Appendix S2). However, the degree of stratification differed, with much higher densities and density gradients observed in the bottom 1–2 m of flows in an active state. These denser basal layers progressively developed on the steeper proximal slope region and became more prominent over the bed-form region (Figs. 2A and 3).

Sediment Transport Regime

Active flow states were characterized by higher Shields numbers, indicating greater near-bed shear stress and sediment mobility (Figs. 2 and 3C; Appendix S2). The higher Shields numbers led to considerable erosion, sediment entrainment, and higher basal sediment concentrations at the base of the slope and into the bed-form region (Figs. 2 and 3). As a result, the denser and faster flows were able to initiate and migrate the upstream-migrating bed forms through bed erosion and deposition, while minimal changes to the bed morphology were observed during the other flow states (Fig. 2; Appendix S4).

DISCUSSION

Dense Flows Initiate Upstream-Migrating Bed Forms

As previously suggested, the bed-form–forming flows represented by the active flow state in simulation trials are Froude supercritical, erosive, and stratified. However, flows that did not initiate bed forms were also Froude supercritical and showed stratification (Figs. 2 and 3). Development of a slope break always preceded bed-form initiation, but its presence did not always trigger bed-form migration (i.e., during the inactive state). Thus, previously hypothesized flow parameters are important but not sufficient to explain bed-form formation.

A clearer relationship was observed between flow state and basal sediment concentration over both the slope and bed-form regions (Fig. 3B). Only flows that developed a denser basal layer (C_b >5 vol%) formed bed forms. These higher sediment concentrations led to stronger gravitational forces ($\sqrt{g'h}$, equation in Appendix S2), which reduced the densiometric Froude number and enabled supercritical flows to temporarily become Froude subcritical and develop hydraulic jumps. The resulting train of hydraulic jumps is consistent with bed forms generated by cyclic step flow instabilities (Parker, 1996; Kostic, 2011).

Implications for Upstream-Migrating Bed Forms along Submarine Channels

These findings support field observations that have inferred the presence of denser basal layers in flows over decameter-scale upstream-migrating bed forms in sandy submarine channels (Hughes Clarke, 2016; Paull et al., 2018; Gwiazda et al., 2022; Normandeau et al., 2022), as well as studies that have interpreted these bed forms as cyclic steps (Kostic, 2011; Hage et al., 2018). Indeed, a comparison to direct measurements from modern channels showed that the modeling results strongly resemble seafloor observations in terms of bed-form morphology and flow characteristics (Fig. 4). Additionally, dilute flows that do not produce bed-form migration have been observed in steep submarine channels (velocities of 0.5–1.5 m/s and flow thicknesses of 3–7 m; Hughes Clarke, 2016), and so they are comparable to the inactive flows modeled here. These similarities provide confidence in the model output despite its inability to incorporate all grain-related processes, which might enhance peak sediment concentrations (Appendix S1). However, our results may not apply to upstream-migrating bed forms observed in finer-grained, lower-gradient settings, where equilibrium flow properties may be markedly different (Fildani et al., 2021).

In modern submarine channels, upstream-migrating bed forms are observed downstream

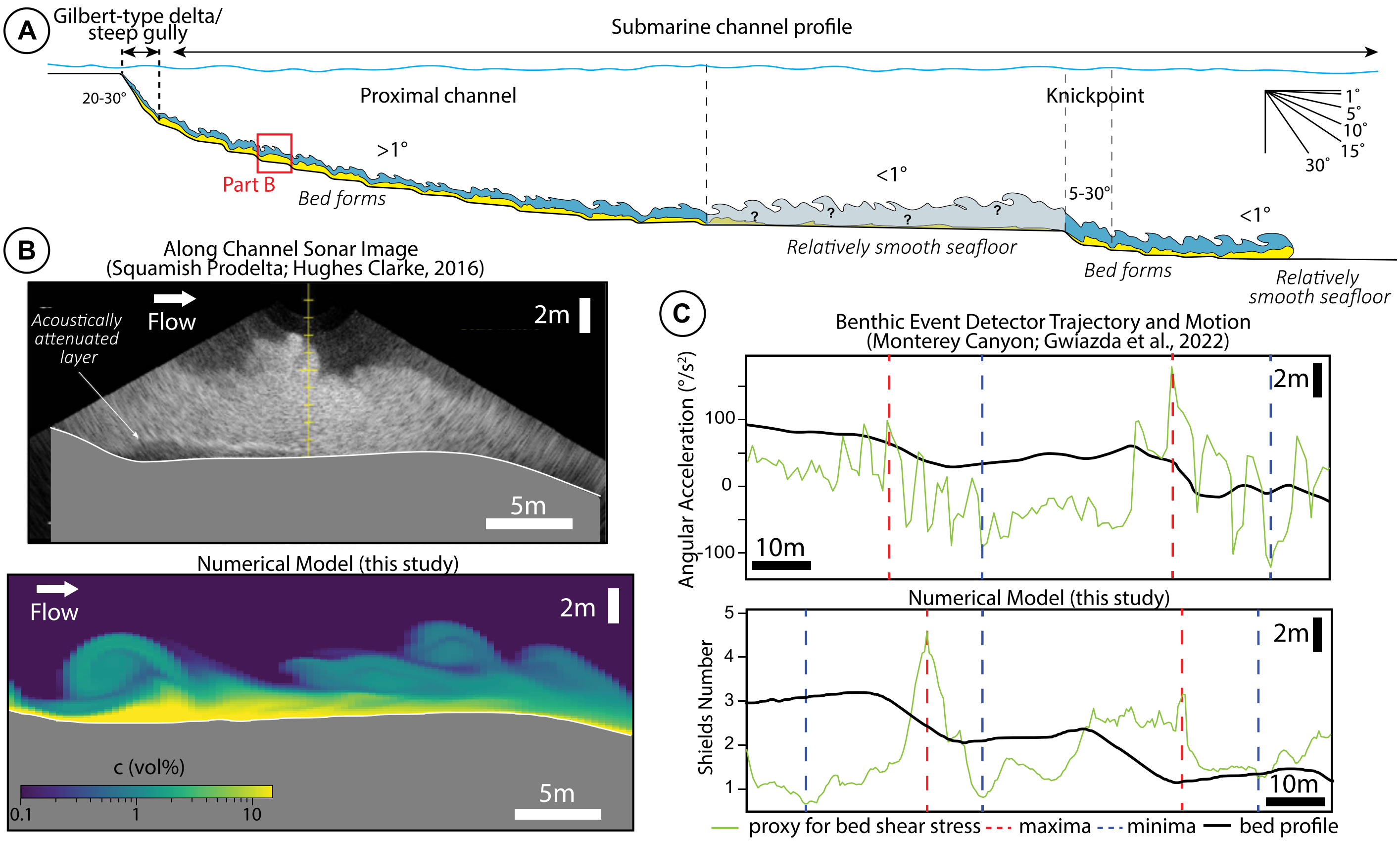

Figure 4. (A) Schematic submarine channel profile where bed forms occur following steep slopes. Nature of flows maintaining bed forms is highlighted in B and C. (B) Along-channel profiles of turbidity current over single bed form, including sonar image from Squamish Prodelta (top) and snapshot of flow sediment concentration field from this study (bottom). Both show 1–2-m-thick denser layer at base of flow, indicated by acoustic attenuation or higher sediment concentrations, which thickens in hydraulic jump in bed-form trough. (C) Comparison of proxies for bed shear stress over bed forms, including angular acceleration measured from boulder-like objects (benthic event detectors) that traveled within a flow in Monterey Canyon (top) and Shields numbers calculated in this study (bottom). In both, high values are observed on bed-form lee slopes and sharply decrease in bed-form troughs and over bed-form stoss slopes.

of steep slopes provided by headwall gullies, Gilbert-type deltas, or knickpoints (Fig. 1). We propose that these steep slopes facilitate erosion and the development of fast, dense turbidity currents that are able to initiate trains of upstream-migrating bed forms downstream, as observed in the model simulations (Fig. 3C). Thus, seafloor gradient provides an explanation for the distribution of bed forms in submarine channels.

CONCLUSIONS

Our model simulations revealed the morphodynamics of turbidity currents that are not obtainable from existing field observations or modeling methods. Surprisingly, not all supercritical turbidity currents triggered the upstream migration of bed forms; rather, upstream-migrating bed forms comparable to those observed in modern sandy submarine channels were only initiated and maintained by flows with high near-bed sediment concentrations (average >5 vol%). This explains the tendency of upstream-migrating bed forms to occur downslope from steep segments in modern submarine channels, which likely promote erosion and allow flows to become denser. Only these fast, sediment-laden turbidity currents have the lower densiometric Froude numbers (Fr_{50} between 1.3–2.2) that are needed to trigger a cyclic step instability and locally achieve Froude subcritical flow conditions. Thus, Froude supercriticality alone is not a sufficient criterion for the formation of sandy, decameter-scale upstream-migrating bed forms. Likewise, it should not be assumed that flows producing smooth, sandy slopes that lack such bed forms are Froude subcritical. Our results highlight the importance of high near-bed sediment concentrations in addition to Froude supercritical conditions in forming decameter-scale upstream-migrating bed forms in steep (>1°), sandy submarine channels.

ACKNOWLEDGMENTS

We thank D. Piper, J. Covault, an anonymous reviewer, and editor K. Benison for constructive reviews that greatly improved the manuscript. This research was supported by ExxonMobil, the National Oceanography Centre, the Natural Sciences and Engineering Research Council of Canada (RGPIN/341715–2013), Netherlands Organization for Scientific Research (NOW; 864.13.006), the Royal Society (DHF/R1/180166), and the Natural Environment Research Council (UK) (NE/L009358/1, NE/P005780/1, NE/P009190/1, NE/S009965/1, NE/S010068/1, NE/R015953/1). Bathymetry data sets were collected by John Hughes Clarke (Bute Inlet, Squamish Prodelta) and the Seafloor Mapping Laboratory of California State University–Monterey Bay (Monterey Canyon, https://seafloor.otterlabs.org/).

REFERENCES CITED

Alexander, J., Bridge, J.S., Cheel, R.J., and Leclair, S.F., 2001, Bedforms and associated sedimentary structures formed under water flows over aggrading sand beds: Sedimentology, v. 48, p. 133–152, https://doi.org/10.1046/j.1365-3091.2001.00357.x.

Balmforth, N.J., and Vakil, A., 2012, Cyclic steps and roll waves in shallow water flow over an erodible bed: Journal of Fluid Mechanics, v. 695, p. 35–62, https://doi.org/10.1017/jfm.2011.555.

Basani, R., Janocko, M., Cartigny, M.J.B., Hansen, W.M., and Eggenhuisen, J.T., 2014, MassFLOW-3D TM as a simulation tool for turbidity currents: Some preliminary results, *in* Martinius, A.W., Ravnås, R., Howell, J.A., Steel, R.J., and Wonham, J.P., eds., From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin: International Association of Sedimentologists Special Publication 46, p. 587–608, https://doi.org/10.1002/9781118920435.ch20.

Cartigny, M.J.B., Ventra, D., Postma, G., Van Den Berg, J.H., and Venditti, J., 2014, Morphodynamics and sedimentary structures of bedforms under supercritical-flow conditions: New insights from flume experiments: Sedimentology, v. 61, p. 712–748, https://doi.org/10.1111/sed.12076.

Chen, Y., Parsons, D.R., Simmons, S.M., Williams, R., Cartigny, M.J.B., Hughes Clarke, J.E., Stacey, C.D., Hage, S., Talling, P.J., Azpiroz-Zabala, M., Clare, M.A., Hizzett, J.L., Heijnen, M.S., Hunt, J.E., Lintern, D.G., Sumner, E.J., Vellinga, A.J., and Vendettuoli, D., 2021, Knickpoints and crescentic bedform interactions in submarine channels: Sedimentology, v. 68, p. 1358–1377, https://doi.org/10.1111/sed.12886.

Covault, J.A., Kostic, S., Paull, C.K., Sylvester, Z., and Fildani, A., 2017, Cyclic steps and related supercritical bedforms: Building blocks of deep-water depositional systems, western North America: Marine Geology, v. 393, p. 4–20, https://doi.org/10.1016/j.margeo.2016.12.009.

de Cala, I., Ohata, K., Dorrell, R., Naruse, H., Patacci, M., Amy, L.A., Simmons, S., McLelland, S.J., and McCaffrey, W.D., 2020, Relating the flow processes and bedforms of steady-state and waning density currents: Frontiers of Earth Science, v. 8, https://doi.org/10.3389/feart.2020.535743.

Fedele, J.J., Hoyal, D., Barnaal, Z., Tulenko, J., and Awalt, S., 2016, Bedforms created by gravity flows, *in* Budd, D.A., et al., eds., Autogenic Dynamics and Self-Organization in Sedimentary Systems: Society for Sedimentary Geology (SEPM) Special Publication 106, p. 95–121, https://doi.org/10.2110/sepmsp.106.12.

Fildani, A., Kostic, S., Covault, J.A., Maier, K.L., Caress, D.W., and Paull, C.K., 2021, Exploring a new breadth of cyclic steps on distal submarine fans: Sedimentology, v. 68, p. 1378–1399, https://doi.org/10.1111/sed.12803.

Gilbert, G.K., 1914, The Transportation of Debris by Running Water: U.S. Geological Survey Professional Paper 86, 263 p., https://doi.org/10.3133/pp86.

Gwiazda, R., Paull, C.K., Kieft, B., Klimov, D., Herlien, R., Lundsten, E., McCann, M., Cartigny, M.J., Hamilton, A., Xu, J., Maier, K.L., Parsons, D.R., and Talling, P.J., 2022, Near-bed structure of sediment gravity flows measured by motion-sensing “boulder-like” benthic event detectors (BEDs) in Monterey Canyon: Journal of Geophysical Research: Earth Surface, v. 127, https://doi.org/10.1029/2021JF006437.

Hage, S., Cartigny, M.J.B., Clare, M.A., Sumner, E.J., Vendettuoli, D., Hughes Clarke, J.E., Hubbard, S.M., Talling, P.J., Lintern, D.G., Stacey, C.D., Englert, R.G., Vardy, M.E., Hunt, J.E., Yokokawa, M., Parsons, D.R., Hizzett, J.L., Azpiroz-Zabala, M., and Vellinga, A.J., 2018, How to recognize crescentic bedforms formed by supercritical turbidity currents in the geologic record: Insights from active submarine channels: Geology, v. 46, p. 563–566, https://doi.org/10.1130/G40095.1.

Hughes Clarke, J.E., 2016, First wide-angle view of channelized turbidity currents links migrating cyclic steps to flow characteristics: Nature Communications, v. 7, https://doi.org/10.1038/ncomms11896.

Hughes Clarke, J.E., Marques, C.R.V., and Pratomo, D., 2014, Imaging active mass-wasting and sediment flows on a fjord delta, Squamish, British Columbia, *in* Krastel, S., ed., Submarine Mass Movements and Their Consequences: Cham, Switzerland, Springer, Advances in Natural and Technological Hazards Research 37, p. 249–260, https://doi.org/10.1007/978-3-319-00972-8_22.

Kostic, S., 2011, Modelling of submarine cyclic steps: Controls on their formation, migration, and architecture: Geosphere, v. 7, p. 294–304, https://doi.org/10.1130/GES00601.1.

Kostic, S., and Parker, G., 2006, The response of turbidity currents to a canyon-fan transition: Internal hydraulic jumps and depositional signatures: Journal of Hydraulic Research, v. 44, p. 631–653, https://doi.org/10.1080/00221686.2006.9521713.

Maselli, V., Micallef, A., Normandeau, A., Oppo, D., Iacopini, D., Green, A., and Ge, Z., 2021, Active faulting controls bedform development on a deepwater fan: Geology, v. 49, p. 1495–1500, https://doi.org/10.1130/G49206.1.

Mastbergen, D.R., and Van Den Berg, J.H., 2003, Breaching in fine sands and the generation of sustained turbidity currents in submarine canyons: Sedimentology, v. 50, no. 4, p. 625–637, https://doi.org/10.1046/j.1365-3091.2003.00554.x.

Meyer-Peter, E., and Müller, R., 1948, Formulas for bed-load transport, *in* Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research: Stockholm, Sweden, International Association for Hydraulic Structures Research, p. 38–64.

Normandeau, A., Lajeunesse, P., Ghienne, J.-F., and Dietrich, P., 2022, Detailed seafloor imagery of turbidity current bedforms reveals new insight into fine-scale near-bed processes: Geophysical Research Letters, v. 49, https://doi.org/10.1029/2021GL097389.

Normark, W.R., Piper, D.J.W., and Hess, G.R., 1979, Distributary channels, sand lobes, and mesotopography of Navy Submarine Fan, California Borderland, with applications to ancient fan sediments: Sedimentology, v. 26, p. 749–774, https://doi.org/10.1111/j.1365-3091.1979.tb00971.x.

Ohata, K., Naruse, H., Yokokawa, M., and Viparelli, E., 2017, New bedform phase diagrams and discriminant functions for formative conditions of bedforms in open-channel flows: Journal of Geophysical Research: Earth Surface, v. 122, no. 11, p. 2139–2158, https://doi.org/10.1002/2017JF004290.

Parker, G., 1996, Some speculations on the relation between channel morphology and channel-scale flow structures, *in* Ashworth, P.J., Bennett, S.J., Best, J.L., and McLelland, S.J., eds., Coherent Flow Structures in Open Channels: London, John Wiley and Sons Ltd., p. 424–458.

Paull, C.K., Ussler, W., Caress, D.W., Lundsten, E., Covault, J.A., Maier, K.L., Xu, J., and Augenstein, S., 2010, Origins of large crescent-shaped bedforms within the axial channel of Monterey Canyon, offshore California: Geosphere, v. 6, p. 755–774, https://doi.org/10.1130/GES00527.1.

Paull, C.K., Caress, D.W., Ussler, W., Lundsten, E., and Meiner-Johnson, M., 2011, High-resolution bathymetry of the axial channels within Monterey and Soquel submarine canyons, offshore central California: Geosphere, v. 7, no. 5, p. 1077–1101, https://doi.org/10.1130/GES00636.1.

Paull, C.K., Talling, P.J., Maier, K.L., Parsons, D., Xu, J., Caress, D.W., Gwiazda, R., Lundsten, E.M., Anderson, K., Barry, J.P., Chaffey, M., O’Reilly, T., Rosenberger, K.J., Gales, J.A., Kieft, B., McGann, M., Simmons, S.M., McCann, M., Sumner, E.J., Clare, M.A., and Cartigny, M.J., 2018, Powerful turbidity currents driven by dense basal layers: Nature Communications, v. 9, p. 4114, https://doi.org/10.1038/s41467-018-06254-6.

Postma, G., and Cartigny, M.J.B., 2014, Supercritical and subcritical turbidity currents and their deposits—A synthesis: Geology, v. 42, p. 987–990, https://doi.org/10.1130/G35957.1.

Shepard, F.P., and Dill, R.F., 1966, Submarine Canyons and Other Sea Valleys: Chicago, Illinois, Rand McNally, 381 p.

Symons, W.O., Sumner, E.J., Cartigny, M.J.B., and Clare, M.A., 2016, Large-scale sediment waves and scours on the modern seafloor and their implications for the prevalence of supercritical flow: Marine Geology, v. 371, p. 130–148, https://doi.org/10.1016/j.margeo.2015.11.009.

Talling, P.J., Allin, J., Armitage, D.A., Arnott, R.W.C., Cartigny, M.J.B., Clare, M.A., Felletti, F., Covault, J.A., Girardclos, S., Hansen, E., Hill, P.R., Hiscott, R.N., Hogg, A.J., Hughes Clarke, J., Jobe, Z.R., Malgesini, G., Mozzato, A., Naruse, H., Parkinson, S., Peel, F.J., Piper, D.J.W., Pope, E., Postma, G., Rowley, P., Sguazzini, A., Stevenson, C.J., Sumner, E.J., Sylvester, Z., Watts, C., and Xu, J., 2015, Key future directions for research on turbidity currents and their deposits: Journal of Sedimentary Research, v. 85, p. 153–169, https://doi.org/10.2110/jsr.2015.03.

Tilston, M., Arnott, R.W.C., Rennie, C.D., and Long, B., 2015, The influence of grain size on the velocity and sediment concentration profiles and depositional record of turbidity currents: Geology, v. 43, no. 9, p. 839–842, https://doi.org/10.1130/G37069.1.

Vellinga, A.J., Cartigny, M.J.B., Eggenhuisen, J.T., and Hansen, E.W.M., 2018, Morphodynamics and depositional signature of low-aggradation cyclic steps: New insights from a depth-resolved numerical model: Sedimentology, v. 65, p. 540–560, https://doi.org/10.1111/sed.12391.

Wynn, R.B., and Stow, D.A.V., 2002, Classification and characterization of deep-water sediment waves: Marine Geology, v. 192, p. 7–22, https://doi.org/10.1016/S0025-3227(02)00547-9.

Printed in the USA