Turbidite models revisited

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Several standard turbidite models have been proposed and acted as norms for the description and interpretation of deep-water stratigraphic successions and analyses of hydrodynamic processes of turbidity currents and their related sediment-gravity flows. Although flume experiments, numerical modeling, and some direct observations of turbidity currents have played important roles in elucidating the origin of component units of the models, formation processes of some component units have continued to rely on theoretical consideration and/or speculation based on their lithofacies features. The models have been established in terms mainly of the combination of grain sizes and sedimentary structures. Although sedimentary structures represent cross sectional views of bedforms, the origin of component units and their vertical successions in turbidites has not necessarily been investigated in terms of bedforms. Thus, incorporation of component elements of a bedform into a turbidite model is challenging for a better understanding of the origin of spatial and temporal variations in lithofacies organization of turbidites. Turbidites which formed in active margin basins are commonly coarser than those in continental margin basins, and are locally associated with conglomerates and pebbly sandstones. In addition, silty turbidites are also common in the uppermost part of classical (sandy/silty) turbidites formed in active margin basins and enable us to investigate the origin of laminated silts and siltstones in fine-grained turbidites.

Conglomerates and pebbly sandstones in turbidite successions have been interpreted to be formed by tractional processes of turbidity currents (*sensu lato*). Thus, their transportation and deposition are likely induced by migration and aggradation of coarse-grained bedforms. Using outcrop analogues of coarse-grained sediment waves, which have been observed in modern deep-water environments, inversely graded, ungraded or stratified, and normally graded conglomerates are interpreted to represent deposits formed in stoss side, central part, and lee side of a coarse-grained sediment wave deposit, respectively. In addition, planar stratified and/or spaced stratified pebbly sandstones, which have been assigned to be formed as traction carpets, show gently undulating waveforms, which gradationally overlie coarse-grained sediment wave deposits or constitute a distinctive bedform by themselves, and are overlain gradationally by ungraded or normally graded pebbly sandstones. Thus, component units of coarse-grained turbidites can best be interpreted to be formed by migration and aggradation of different parts of coarse-grained sediment waves.

The origin of laminated silts and siltstones in the uppermost part of classical turbidites still remain controversy, and has been supposed to be a result of shear shorting of silts and clay flocs. This process, however, was proposed to explain the formation of laminated muds and mudstones in the basal part of turbiditic muds and mudstones, and is not necessarily suitable for explaining the origin of laminated silts and siltstones. Detailed outcrop observations indicate that silt lamination commonly occurs as sinusoidal lamination over the underlying current-ripple cross-lamination, and distinct grain size breaks are obvious within the laminated siltstones in the stoss sides while gradational fining is common in the lee sides. Long axes of silt grains on the lamina planes is aligned nearly orthogonal to the paleocurrents in the lower part and gradationally changes to become nearly parallel to the paleocurents in the upper part of the laminated siltstones in response to fining and the increase in clay contents. Thus, laminated silts and siltstones are likely to have formed as a response to the development of low-amplitude sinusoidal bedforms over current ripples with an increased rate of suspended load deposition in turbidity currents.

Keywords: turbidite models, coarse-grained turbidites, coarse-grained sediment waves, fine-grained turbidites, laminated siltstones

Bedform and grain size variation in Froude supercritical flow deposits: Field examples of conglomerates, sandstones and fine-grained turbidites in deepwater slope settings.

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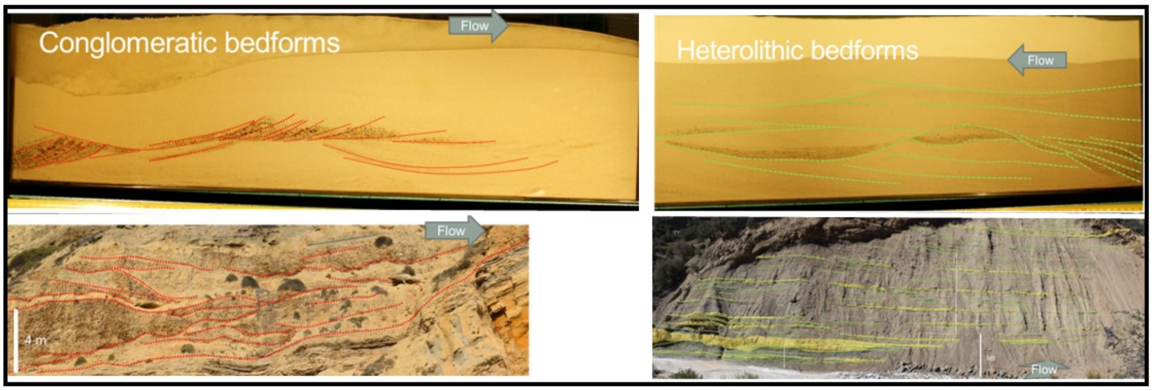
There is a growing body of evidence for Froude supercritical flow bedforms from modern subaqueous steep slopes, from deltaic settings to deepwater continental slopes. Froude supercritical flow bedforms have also been documented in subaerial alluvial to fluvial settings. Morphodynamics of supercritical flow bedforms and their deposits are well established by flume experiments. However, outcrop recognition of Froude supercritical flow sedimentary structures and geometries in those subaqueous settings has not yet been well established. Their recognition in the field is complicated by the various scales of supercritical flow bedforms (e.g., backsets and scour and fill structures), where multi-meter to tens of meters thick bedforms are built by smaller-scale bedforms on centimeter to a meter scale. The large-scale supercritical flow bedform wavelength is characteristically on 10’ s to 100 meter scale, and thus the complete bedforms are hard to observe unless the outcrop scale is large. These bedforms have commonly erosional set boundaries, as well as contain internal discordances, and are therefore easily confused with channels. Furthermore, they are formed in various grain sizes ranging from cobble-conglomerate to silty fine-grained deposits, with characteristic grain size trends, such as upward fining, downstream-and-upstream sharp grain-size contacts but gradual lateral changes.
This paper aims to describe supercritical flow sedimentary structures from ancient active margin deepwater continental slopes exemplifying differences between the erosionally bound large-scale bedforms and their host channels that are an order of magnitude larger. We also discuss their morphodynamics based on new experiments conducted with various grain sizes, ranging from silt to granules. We compare the experimental results and outcrop examples, and demonstrate that variable grain sizes provide more complex geometries than the single-grain size supercritical flow bedforms.

Keywords: Froude supercritical flow, deepwater slope, bedform



Upper pictures exhibit the complex scour-fill-structures formed under supercritical flow condition.
The lower pictures are from the outcrop examples from Eocene deepwater slope channnel complex.

Marine and terrestrial biomarker analyses of hemipelagite in the Pleistocene Kazusa forearc basin: Evaluation of the effect of turbidity current

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Hemipelagic muddy sediments (hemipelagite) are mainly deposited by the interplay of continuous vertical settling, and advection of fine-grained clastic and biogenic particles superimposed by turbidity currents and some other deep-water currents. The effects of turbidity currents in the hemipelagic sedimentation processes, however, have not yet clearly investigated. In the present study, we conducted organic geochemical analyses, such as total organic carbon content (TOC), bulk organic carbon isotope ratios ($\delta^{13}C_{org}$), and biomarker compositions in some age-equivalent hemipelagic siltstone beds, which are locally intercalated with turbidite sandstone beds, to evaluate the effect of turbidity currents in hemipelagic sedimentation.

Samples were collected from two series of the age-equivalent hemipelagites in the Kiwada Formation, Boso Peninsula, Japan. This formation is mainly composed of siltstones intercalated with turbidite sandstones and volcanic ash beds, and is interpreted to have deposited in slope to basin-plain settings in the Kazusa forearc basin. In the studied succession, turbiditic sandstones and siltstones gradational fine-upward to bioturbated hemipelagic siltstones and is intercalated with a volcanic ash bed named Kd8 (ca. 1.2 Ma), which consists of three volcanic ash beds, tentatively named herein as Kd8A to Kd8C in descending. These ash beds can be mapped for over 30 km from the proximal (SW) to distal (NE) environments. The samples were obtained from upper (U) and lower (L) parts of the two siltstone beds named Kd8a and Kd8b, which are encased between Kd8A–B and KdB–C, respectively. A turbiditic sandstone and siltstone bed is developed just beneath the Kd8b in the most distal area, indicating that hemipelagic sedimentation for Kd8b-L may have been affected by turbidity currents.

The TOC contents of the siltstones just above the turbidite bed (Kd8b-L) are lower (TOC = 0.23 %), and the $\delta^{13}C_{org}$ values of these siltstones are lighter (-23.3 ‰) than those in the overlying siltstones (-21.3 ‰). These variations likely indicate inefficient deposition of organic matter in association with higher contribution of terrigenous organic matter.Concentrations of friedelin, which is a plant triterpenoid and derived mainly from tree bark, in the TOC are also remarkably higher in the same siltstone samples. These results suggest that turbidity currents may have contributed to the deposition of terrigenous organic matter during hemipelagic sedimentation and the lower TOC content are considered to have been resulted from preferential deposition of siliciclastic clastic particles.The lower $\delta^{13}C_{org}$ values and higher concentrations of friedelin observed in the Kd8b-L in several sites are also likely a result of fine-grained sediment supply from turbidity currents. On the other hand, the Kd8b-L are obviously lower TOC contents in the all study sites. In addition, the long-chain *n*-alkanol (> C_{20}) distribution maximizing at C_{26} and C_{28} are found in all siltstone sampled from the Kd8b-L, while that in siltstone samples from the other beds show abundant C_{22} and C_{24} *n*-alkanols as well as C_{26} and C_{28} homologues. Although long-chain *n*-alkanols in marine sediments are generally considered to be derived from higher plant wax, several zooplankton species such as copepod also contain the C_{22} and C_{24} *n*-alkanols. Thus, the distinctive distribution of the long-chain *n*-alkanol in the Kd8b-L can be attributed to selective deposition of plant leaves by the fractionation of organic matter from turbidity currents. The present study indicates that the combination of biomarkers can be used for the evaluation of contribution of turbidity currents to hemipelagic sedimentation.

Keywords: Turbidite, Hemipelagite, Biomarker

Capturing passing hyperpycnal turbidity currents in a submarine canyon after a typhoon

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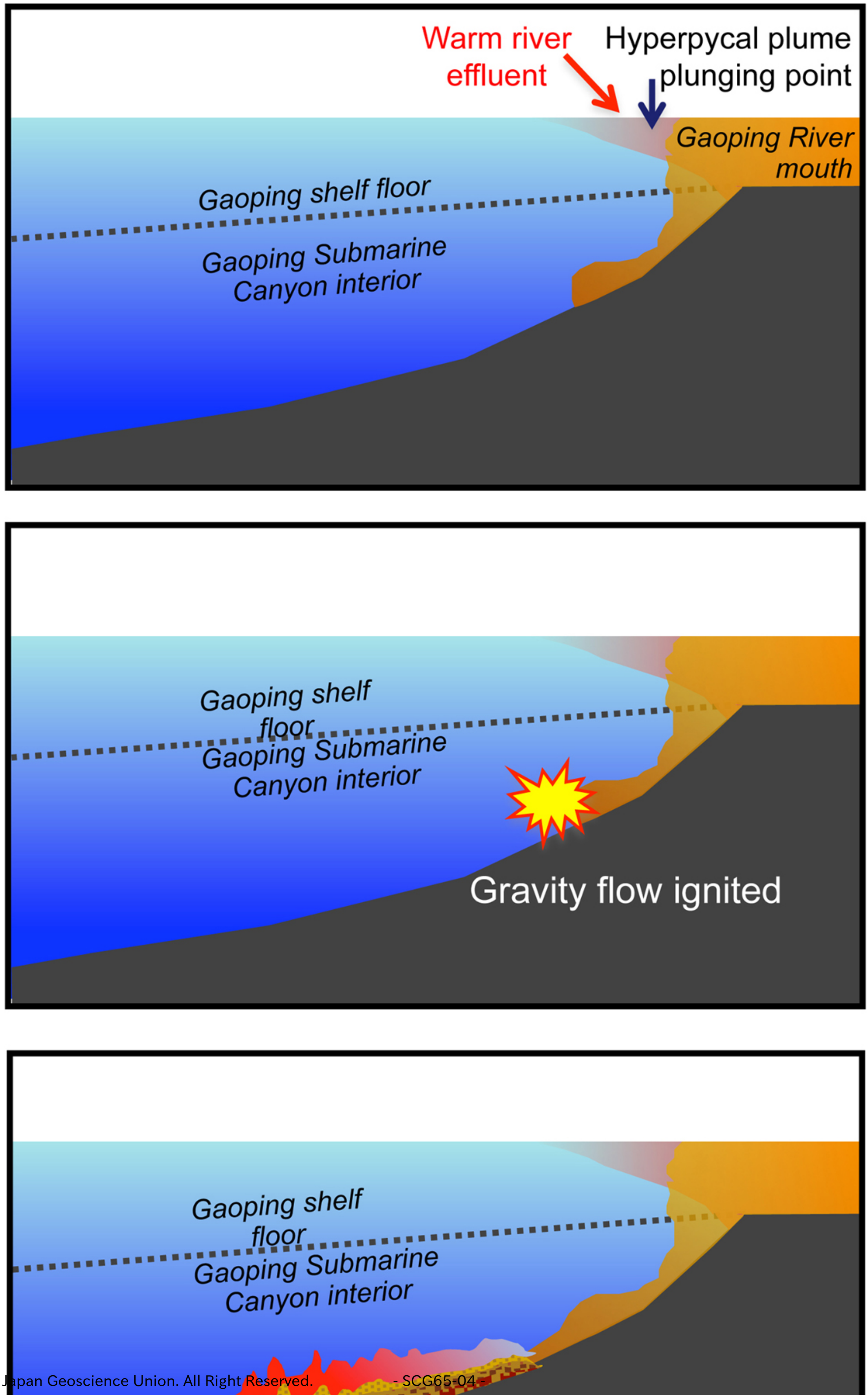
Two hyperpycnal turbidity-current events over 16 hours were captured by two moorings in a submarine canyon 650 m from the surface. One mooring was configured with temperature censors, one acoustic current meter, and a non-sequential sediment trap. The other mooring was configured with an upward-looking long-ranger ADCP. The observed turbidity currents were triggered by typhoon floods of the river that feeds into the canyon. The thickness of the currents was 140 m having max. down-canyon velocity of 1.6 m at the head of the turbidity current. They carried warm water from the surface and terrestrial sediment and organic carbon. Our findings confirms the link between typhoon-tirggered hyperpycnal plume at the mouth of a small mountainous river and the turbidity currents in a nearby submarine canyon that forms an efficient conduit to transport large amount of sediment and organic carbon to the deep-sea.

Keywords: typhoon, hyperpycnal turbidity current, small mountainous rivver, submarine canyon


Warm river effluent
Hyperpycal plume plunging point
Gaoping River mouth
Gaoping shelf floor
Gaoping Submarine Canyon interior
Gaoping shelf floor
Gaoping Submarine Canyon interior
Gravity flow ignited
Gaoping shelf floor
Gaoping Submarine Canyon interior

Two different sources of turbidity currents along the southern Ryukyu forearc

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There is a series of forearc basins deepening eastward along the southern Ryukyu islands to East of Taiwan. To understand the depositional processes of the southern Ryukyu forearc area and to obtain more precise recurrence interval of turbidite deposition, we collected sediment cores from the forearc basins. A core collected from a terminal forearc basin at SW of Iriomote Island contained thick and massive muddy turbidites with sharp erosional basal contact and thin sandy layer composed of lithic fragments. Similar but thin-bedded muddy turbidites occurred in the cores from the Ryukyu Trench floor. Two cores from a further east forearc basin also intercalates with the similar muddy turbidites but also with thick calcareous sandy beds with chaotic structures. On the other hand, many turbidite beds composed of bioclastic carbonate grains were intercalated in calcareous silt in the cores obtained from a small submarine fan at the mouth of a submarine canyon at SW of Ishigaki Island, further east of the terminal forearc basin. Comparison of lithology of four cores from the fan indicated the temporal shift of depocenter of turbidites. This suggests that at least some cores need to reconstruct the depositional history of the turbidites on the submarine fan. Bathymetric characteristics of the southern Ryukyu forearc suggests that most probable origin of the clastic muddy turbidite is Taiwan, and that of the coarse bioclastic sandy turbidite is coastal area of the southern Ryukyu islands. High rate of uplift of central Taiwan might contribute frequent generation of turbidity currents, which supply large amount of fine-grained sediments toward East to the southern Ryukyu forearc and Ryukyu Trench.

Keywords: turbidite, Ryukyu arc, Taiwan

Direct Measurement of Field Turbidity Currents: Preliminary Results of the Monterey Coordinated Canyon Experiment

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Turbidity currents flowing through submarine canyons are among the most important sediment transport processes on Earth. When compared to other sediment transport processes such as rivers that have been monitored on regular bases for many years (e.g. USGS gauging network), there are very few direct measurements of turbidity currents in action. However, technological advances in recent years now have allowed us to directly measure the hydraulic and sedimentological properties of turbidity currents. The Coordinated Canyon Experiment (CCE) was designed to do just that - to capture field turbidity current events in Monterey Canyon, offshore California. A total of 6 moorings that hosted instrument packages including acoustic Doppler current profilers (ADCPs), temperature and salinity sensors, turbidity sensors, and sediment traps were distributed from 270 to 1,850m water depths along the axis of the canyon. In addition, an array of benthic event detectors (BEDs) that record the canyon floor movements were deployed in the shallow reaches of the canyon. During the first two deployments (2015/10 –2016/4; 2016/4 –2016/10), at least 2 turbidity currents were recorded to run out for more than 50km, passing through all 6 moorings with average velocities of 5.4 and 4.2m/sec respectively. Individual moorings and instruments were transported down-canyon up to 7.8 km in one event. This talk will present some highlights of the recorded turbidity currents and discuss the preliminary findings from this rare CCE dataset.

Keywords: Turbidity currents, Monterey Canyon, Sediment transport, in-situ measurements

Direct observation of knick point acitivity in turbidity current channels

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High-resolution bathymetric images of turbidity current channels reveal the existence of a wide range of bedforms within these systems. Knick points are the dominant bedform on a kilometre scale in most sandy systems. These knick points are thought to initiate and maintain submarine channels, and they would therefore play a key role the transport of sediment and nutrients to the deep sea. In contrast to their important role very little is known about knick points. What drives the formation of a knick point? Are they remnant headwalls of landslide, or are they related to turbidity currents? Are they a purely erosional feature? Do they have any preservation potential in the rock record?

Here we present data collected from knick points in an active turbidity current channel on a fjord floor in British Colombia, Canada. These data show how trains of knick points migrate several hundred metres upstream every year. We use repeat surveys to show how knick points are a combined erosional-depositional feature. Furthermore, we have deployed several instruments over the knick points to study how the knick points interact with the passing turbidity currents. Finally, we use repeat surveys and cores to explore the potential architecture and facies association associated to knick points.

Keywords: Turbidity currents, submarine channels, knick points

Numerical Modeling of Turbidity Currents in Various Environments

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Numerical modeling is frequently combined with physical experiments and/or field observations to improve our understanding of the formation, propagation, and depositional patterns of turbidity currents in different environments. This talk addresses the main challenges associated with numerical modeling of turbidity currents. My numerical model of progradational fan-deltas is used to illustrate the importance and complexity of boundary conditions. My numerical model of ponding turbidity currents in salt withdrawal minibasins is compared to numerical models of turbidity currents cascading over a series of depression to demonstrate that a) numerical modeling entails in-depth understanding of underlying physics (e.g. turbulence in minibasins is dead or dying, which has to be accounted for via water detrainment); and b) the common practice to calibrate and verify numerical models based solely on bed elevation profiles can be very misleading. My model of internal hydraulic jumps is used to illustrate that models validated against experimental studies often cannot be directly applied to field-scale problems. Numerical experiments with my model of upper-flow regime bedforms pertain to the morphodynamic interaction between turbidity currents and upstream marching bedforms in channels on the active Squamish prodelta. They are used to demonstrate that even date from extensive monitoring programs can often lack some crucial information for numerical modeling. This talk also explores problems associated with using "black box" commercial software, and the discrepancy between available data and expected results from numerical simulations, in particular with 3-D and other complex models.

Keywords: turbidity currents, numerical modeling, calibration and verification, boundary conditions, 3-D models , commercial software

Threshold conditions for occurrence of tsunami-generated turbidity currents: examination by 2D numerical experiments

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This study aims to investigate the conditions for generating turbidity currents due to the sediment entrainment by large-scale tsunamis. The occurrence of the tsunami-generated turbidity current was suggested by the sudden displacement of the ocean bottom pressure meter (OBP) which was situated on the sea floor offshore Sanriku-Coast, northern Japan. On the basis of this displacement of the OBP and the observation of the sea floor, Arai et al. (2013) proposed the hypothesis that the 2011 Tohoku-Oki Tsunami generated the turbidity current on the submarine slope. They inferred that the tsunami run-up and backwash flows caused the suspended sediment cloud by entrainment of basal sediment, and that the turbidity current was then developed from the sediment cloud. However, the detailed development processes and conditions for generating turbidity currents by tsunamis have not been clarified yet. Therefore, we conducted the numerical experiments using the two-dimensional RANS model that employed the renormalized group k-epsilon turbulence model. In our experiments, the digital elevation model of the submarine slope offshore Sanriku-Coast was used for the experimental topography. The suspended sediment clouds were initially allocated on the upstream end of the slope, and the time evolution of the flow for 10,000 seconds were calculated by the model. We conducted the experiments repeatedly, changing the initial heights, lengths and sediment concentrations of the suspended sediment cloud. As a result of our experiments, it was suggested that a threshold condition for generating turbidity currents from the suspended sediment cloud clearly exists. The suspended clouds larger than 30 m for the initial height and more than 0.05w.% for the initial concentration produced intense turbidity currents that often exceeded 10 m/s for the maximum velocity. On the other hand, no flow occurred in the cases where the initial heights of the sediment cloud were less than 20 m. These contrasting results were caused by the self-accelerating process of turbidity currents. The suspended sediment clouds above the threshold condition were accelerated by the increase of density due to the entrainment of basal sediment, whereas those below the threshold condition were decelerated because it could not erode substrate sufficiently. Our results suggest that the tsunami-generated turbidity currents also have a threshold conditions for occurrence corresponding to scales of tsunamis. Thus, it is inferred that the tsunami-generated turbidites only record exceptionally large tsunamis beyond the threshold condition, of which recurrence intervals could be in millennial scales.

Keywords: turbidite, turbidity current, tsunami

High-resolution Simulations of Turbidity Currents

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1. University of California Santa Barbara

We employ direct numerical simulations of the three-dimensional Navier-Stokes equations to investigate the interactions of bidisperse turbidity currents with three-dimensional seafloor topography in the form of Gaussian bumps. We compare results for two different bump heights against currents propagating over a flat surface. The bump heights are chosen such that the current largely flows over the smaller bump, while it primarily flows around the taller bump. Furthermore, the effects of the settling velocity are investigated by comparing turbidity currents with corresponding compositional gravity currents. The influence of the bottom topography on the front velocity of turbidity currents is seen to be much weaker than the influence of the particle settling velocity. Consistent with earlier work on gravity currents propagating over flat boundaries, the influence of the Reynolds number on the front velocity of currents interacting with three-dimensional bottom topography is found to be small, as long as the Reynolds number is larger than O(1,000). The lobe-and-cleft structures, on the other hand, exhibit a stronger influence of the Reynolds number. The current/bump interaction deforms the bottom boundary-layer vorticity into traditional horseshoe vortices, with a downwash region in the centre of the wake. At the same time, the vorticity originating in the mixing layer between the current and the ambient interacts with the bump in such a way as to form 'inverted horseshoe vortices', with an upwash region in the wake centre. Additional streamwise vertical structures form as a result of baroclinic vorticity generation. The dependence of the sedimentation rate and streamwise vorticity generation on the height of the bump are discussed, and detailed analyses are presented of the energy budget and bottom wall-shear stress. It is shown that for typical laboratory-scale experiments, the range of parameters explored in the present investigation will not give rise to bedload transport or sediment resuspension. Based on balance arguments for the kinetic and potential energy components, a scaling law is obtained for the maximum bump height over which gravity currents can travel. This scaling law is validated by simulation results, and it provides a criterion for distinguishing between 'short' and 'tall' topographical features. For turbidity currents, this scaling result represents an upper limit. An interesting non-monotonic influence of the bump height is observed on the long-term propagation velocity of the current. On the one hand, the lateral deflection of the current by the bump leads to an effective increase in the current height and its front velocity in the region away from the bump. At the same time, taller bumps result in a more vigorous three-dimensional evolution of the current, accompanied by increased levels of dissipation, which slows the current down. For small bumps, the former mechanism dominates, so that on average the current front propagates faster than its flat bottom counterpart. For currents interacting with larger bumps, however, the increased dissipation becomes dominant, so that they exhibit a reduced front velocity as compared to currents propagating over flat surfaces.

Furthermore, particle-resolving simulations of erosion and deposition will be discussed as well. In these simulations the Navier-Stokes flow around each particle is resolved by means of an immersed boundary method, and the particle/particle interactions are accounted for via a detailed collision model.

Keywords: turbidity current, Navier-Stokes simulation, grain-resolving simulation

Bed instability generated by turbidity currents

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Once relatively fine sediment is entrained into water on the ocean floor of the continental shelf or the continental slope, water near the ocean floor increases its density due to the entrained sediment, and starts to flow in the downslope direction. This density flow is called a turbidity current in particular. A turbidity current has unimaginably high capabilities for erosion of the bed and sediment transport, and therefore, it is one of the major agents for the formation of submarine morphology such as submarine canyons and bedforms. As turbidity currents transport not only sediment also a large amount of organic matters originated in the continental areas to the deep ocean floor, they are one of the most essential processes for the generation of petroleum and methane hydrate. In addition, turbidity currents cause destructive damages on submarine infrastructure such as submarine cables. Therefore, study on turbidity currents is important from view points of the maintenance of submarine infrastructure.

A totally 3000 km long submarine delta thought to be formed by turbidity currents is confirmed to lie on the vast ocean floor from the Bay of Bengal to the Indian Ocean. It had not been known for long how turbidity currents can travel this long distance. In the case of saline or thermal density flow, it increases the thickness due to the entrainment of surrounding water as it flows down the slope, decreases the concentration of suspended sediment, and ends up with extinction. On the other hand in the case of turbidity currents, Luchi (2015) has shown that the layer of high-concentrated suspended sediment (referred to as a high-concentrated layer, hereafter) is not diffused out because of the balance between the settling of sediment and the diffusion of sediment; a normal flow condition can be achieved in the high-concentrated layer. This finding can explain that turbidity currents can travel as far as the ocean floor is inclined. In addition, the existence of normal flow conditions facilitates theoretical analyses on the formation of a variety of submarine morphologies.

In this study, we propose a linear stability analysis of bed waves formed due to instability between the ocean floor and turbidity currents with the use of the assumption of normal flow conditions and a simple turbulent model of the mixing length hypothesis. In the analysis, we employ the flow equations including the concentration of suspended sediment as the driving force, the dispersion/diffusion equation of suspended sediment, and the continuity equation describing the time variation of the bed elevation. Normalizing those governing equations, we obtain two important non-dimensional parameters: the densimetric Froude number and the settling velocity normalized by the shear velocity. If the normalized settling velocity is larger than 0.08, we obtain an unrealistic result that the concentration of suspended sediment vanishes at the top of the high-concentrated layer. This might mean that the high-concentrated layer in the normal flow condition cannot be achieved when sediment is too coarse.

We introduce perturbation on the velocity, the suspended sediment concentration, and the elevations of the bed and water surfaces, and perform a linear stability analysis. It is found that the flat ocean floor becomes unstable in the range of the densimetric Froude number larger than 0.5 to 0.8, and that the dominant wavenumber ranges from 0.3 to 0.5. In addition, bed waves with large wavenumbers migrate downstream while those with small wavenumbers migrate upstream. This result is consistent with experimental results.

Keywords: turbidity currents, bed instability, linear stability analysis

Framework for tying the fluid mechanics of turbidity currents to the excavation of submarine canyons

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The field of erodible-bed morphodynamics, in which the flow interacts with the bed to create morphologic structure and change, has its origins in the study of alluvial rivers. Such morphodynamic analysis has served to characterize the formation of such features as dunes, antidunes, alternate bars, meander point bars, upward-concave long profiles and patterns of sediment sorting. In the case of alluvial rivers, the sediment is assumed to be non-cohesive and loose, with no limitation on mobility imposed by cohesion or lithification. It is only in the present century that the morphodynamic formulation necessary to handle bedrock rivers has been developed. In the case of mixed bedrock-alluvial rivers, the bed is assumed to be lithified bedrock with an intermittent and discontinuous cover of alluvium. If this alluvium is gravel, then the bed can be abraded due to collisions between rolling or saltating grains and the bed. One such morphodynamic formulation is the MRSAA (Macro-Roughness based Saltation-Abrasion-Alluvium) Model. This formulation and related formulations have been used to study the evolution of incisional long profiles in uplifting basins, below-capacity alternate bars moving over bedrock (and incising it), bedrock grooves, alluvial-bedrock bend migration and canyon formation. Yet the largest canyons in the world were excavated not by rivers, but by submarine turbidity currents. The research body on the morphodynamics of submarine canyons is relatively small. Early attempts have involved the assumption that the sediment of the canyon bed is loose, non-cohesive material. The substrate being eroded, however, is likely to have lithified to some degree, or may consist of continental shelf-slope mud that has developed considerable strength. Here we define a framework for treating the morphodynamics of incision in submarine canyons.

Keywords: bedrock, morphodynamics, submarine canyons, turbidity currents

