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.

キーワード：タービダイトモデル、粗粒タービダイト、粗粒セディメントウェーブ、細粒タービダイト、平行葉理シルト岩
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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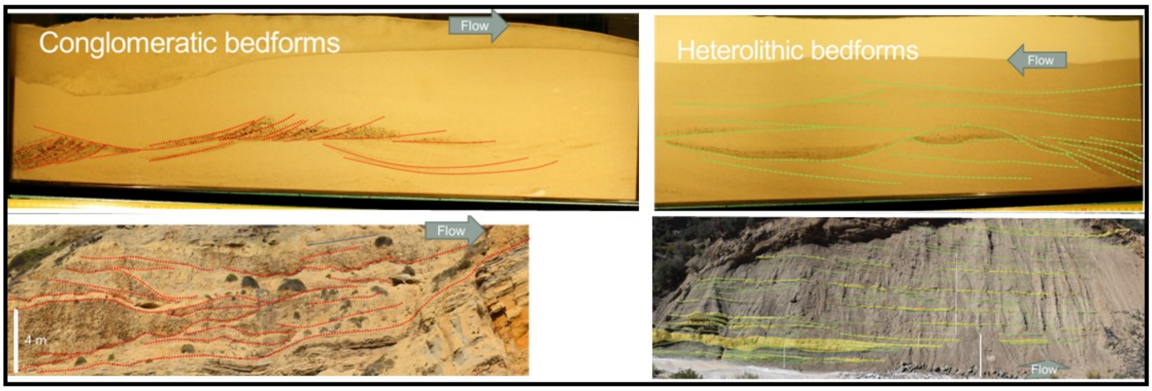
There is a growing body of evidence for Froude supercritical flow bedforms from modern subaqueous steep slopes, from deltaic settings to deepwater continental slopes. Froude supercritical flow bedforms have also been documented in subaerial alluvial to fluvial settings. Morphodynamics of supercritical 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 channel 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.

キーワード：タービダイト、半遠洋性泥、バイオマーカー
Keywords: Turbidite, Hemipelagite, Biomarker

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

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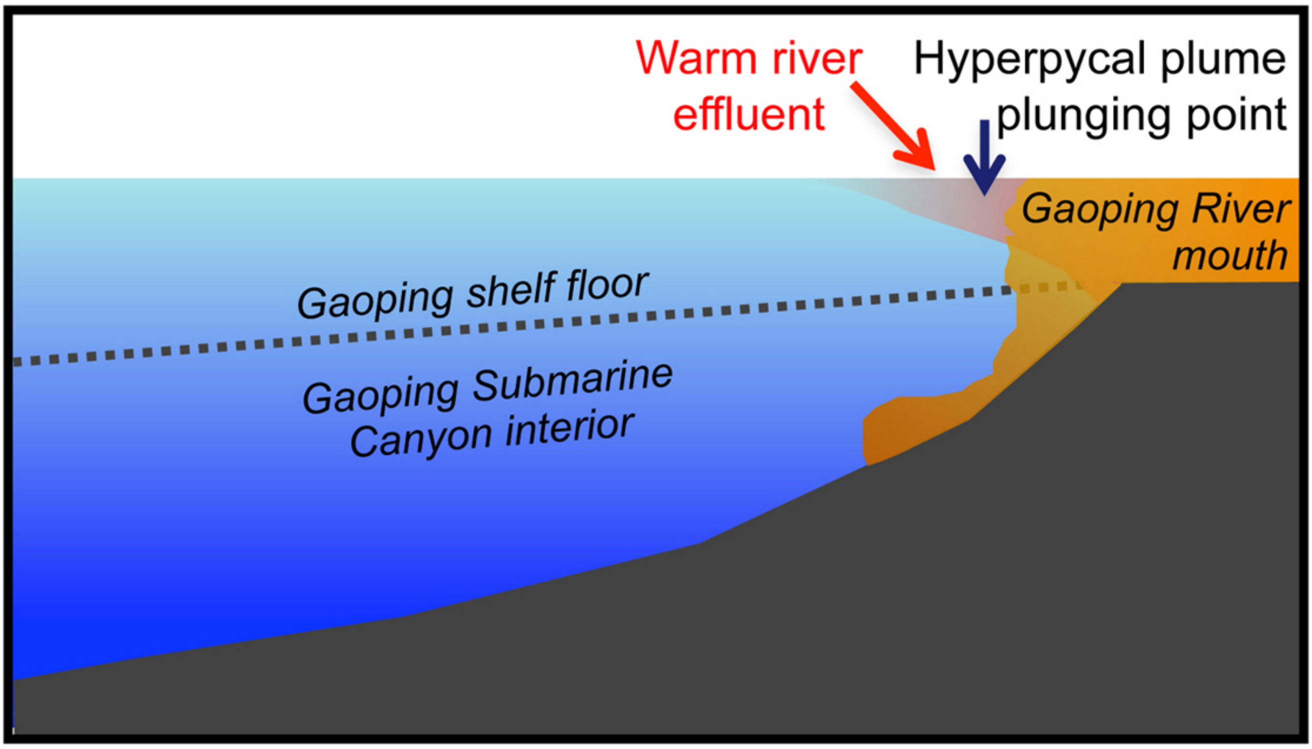
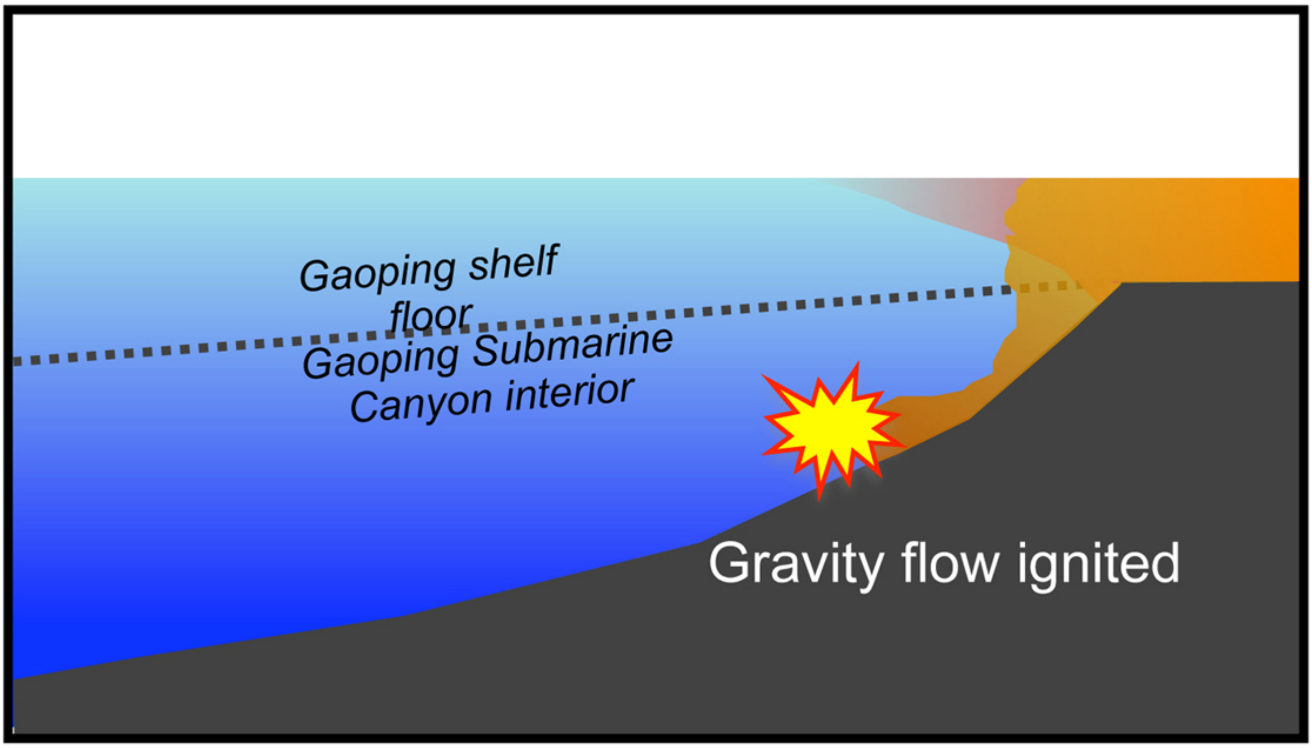
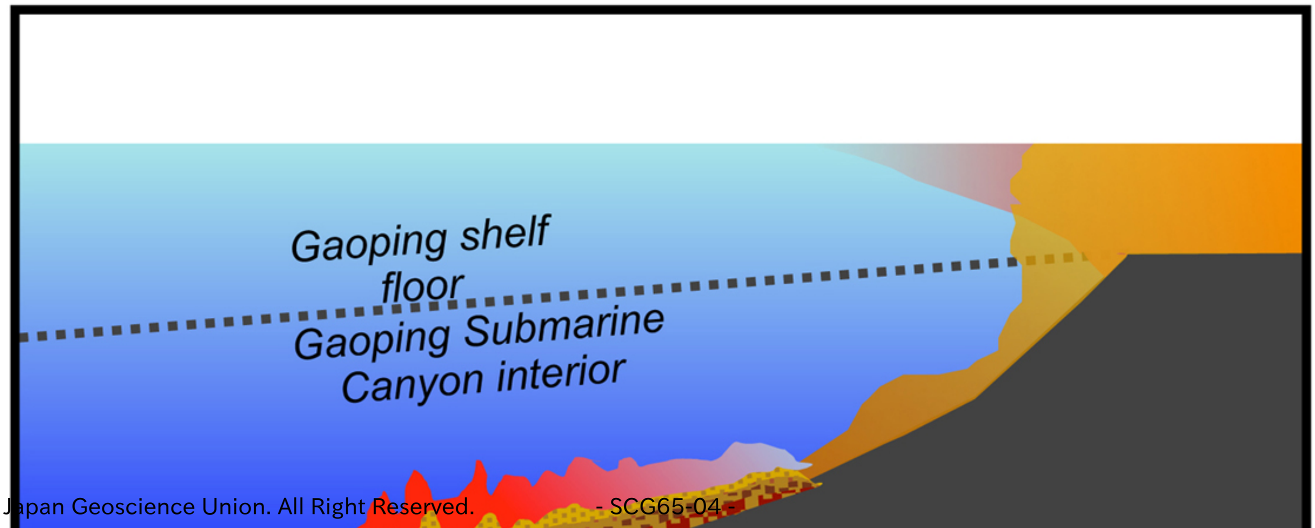
Two hyperpycnal turbidity-current events over 16 hours were captured by two moorings in a submarine canyon 650 m from the surface. One mooring was configured with temperature censors, one acoustic current meter, and a non-sequential sediment trap. The other mooring was configured with an upward-looking 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

琉球諸島南部前弧域にみられる混濁流の2つの起源
Two different sources of turbidity currents along the southern Ryukyu forearc

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琉球諸島南部前弧域には砕屑性の泥質タービダイトと石灰質生物源の砂質タービダイトが存在する。泥質タービダイトは海域の西側に分布し、石灰質砂質タービダイトは琉球諸島側の海底谷沿いに分布する。海底地形から砕屑性泥質タービダイトは台湾から、石灰質砂質タービダイトは琉球諸島側から供給されたと考えられる。台湾の隆起は頻繁な混濁流の発生を起こし、大量の砕屑物を琉球諸島南部前弧域や琉球海溝に供給している。

キーワード：タービダイト、琉球弧、台湾
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

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.

キーワード：タービダイト、混濁流、津波
Keywords: turbidite, turbidity current, tsunami

High-resolution Simulations of Turbidity Currents

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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

混濁流によって発生する底面不安定現象
Bed instability generated by turbidity currents

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大陸棚や大陸斜面上の砂が何らかの原因によって巻き上がると，巻き上がった砂によって底面付近の海水の密度は周囲の水より大きくなり，その海水は斜面下流側に流下し始める．このように，砂を含むことによって密度を増加させ流れる密度流のことを特に混濁流と呼ぶ．混濁流は想像を遥かに超える侵食力や土砂輸送能力を持っており，海底峡谷や海底ベッドフォームなど海底地形を形成する主要な営力となっている．また，土砂だけでなく陸域由来の大量の有機物を深海に輸送しており，石油やメタンハイドレートの生成には無くてはならない重要なプロセスとなっている．さらに混濁流は，大陸間の情報通信に無くてはならない海底ケーブルを切断するほどの大きな破壊力を有しており，海底インフラを維持管理する観点からも重要な問題である．

ベンガル湾からインド洋に広がる海底では，混濁流の堆積によって形成されたと推測される全長3000キロメートルを超えるデルタの形成が確認されているが，これまでこれだけの距離を混濁流が流下し得るメカニズムについては長年の間謎であった．塩水密度流や温度密度流などの密度流では，流下に伴う上部の水の連行によって層厚を増加させ濃度を減少させていく．それに対して混濁流の場合，砂の沈降が拡散と釣り合うことによって，特に濃度の高い層（以降高濃度層と呼ぶ）の拡散が妨げられ，いわゆる等流状態が実現することで，長距離を流下する可能性がLuchiら(2015)によって示されている． もし混濁流に等流状態が存在するとすれば，海底面に傾斜が存在する限り海底面を流下することが可能である．それによって3000キロを超えるようなデルタの形成も合理的に説明することが可能となる．さらに，これまで等流状態が存在しないことで解析が困難となり，近似的な解析にとどまっていた各種海底地形の形成に関する理論解析は飛躍的に容易になる．

以上のことを踏まえて，本研究では等流状態の混濁流の実現を仮定し，乱流モデルとして非常に簡易な混合距離モデルを用いることで海底面に発生する不安定現象によるベッドウェーブの形成に関する線形安定解析を提案した．解析では，浮遊砂濃度をドライビングフォースとする流れの方程式と，浮遊砂の移流拡散方程式，浮遊砂の堆積巻き上げによって生じる海底面高さの時間変化を表す式を支配方程式として用いた．支配方程式を無次元化することで，重要な無次元パラメータが密度フルード数と摩擦速度で無地原価した沈降速度であることが明らかとなった．また，無次元沈降速度が０．０８を上回ると高濃度層の上部に，濃度ゼロの部分が発生するという非現実的な結果となる．浮遊砂の粒径が大きく，摩擦速度に対して沈降速度が大きくなると，等流状態の混濁流は存在しなくなることを意味していると考えられる．

流速および浮遊砂濃度，底面高さ，高濃度層厚に対して摂動を与え線形安定解析を行ったところ，密度フルード数が０．５～０.８より大きい領域で平坦面は不安定となることが明らかとなった．層厚で無次元化した卓越波数は０．３から０．５程度となることが示された．また，河床波は波数の大きい領域では下流に伝搬し，波数の小さい領域では上流に伝搬することが明らかとなった．この結果は実験結果とも一致している．

キーワード：混濁流、底面不安定現象、線形安定解析
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