Morphodynamics of downstream fining in rivers with a unimodal sand-gravel feed

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Over sufficiently long distances, the bed sediment of rivers most commonly becomes finer in the downstream direction. There appears to be no single driver for this. The chief drivers are often thought to be abrasion and selective deposition of coarser material. Downstream fining may be accompanied by a transition point, or transition reach from a gravel-bed to a sand-bed configuration. In some cases such transitions may be relatively sharp, but in other cases they may be more diffuse. The transition itself has been attributed to a) breakdown of clasts into constituent crystals b) depletion of the gravel through deposition, c) damped collisional abrasion of finer grains, and d) rainout of sand from suspension. Here we explore downstream fining using an input sediment that is purely unimodal. Any gravel-sand transition should be produced purely by the internal interactions in the model. The model focuses on the interaction of grains of different sizes, ranging from fine sand to cobbles. The following assumptions are used. 1. The input sediment is taken to be an undifferentiated mixture of sand and gravel with no bi- or multi-modality. 2. Abrasion and other kinds of grain breakdown are neglected. 3. The long profile of the river is assumed to consist of a channel and a floodplain, and is assumed to be undergoing slow subsidence. 4. Sediment conservation is specifically accounted for in all grain size ranges. 5. Relations for bedload transport and sediment suspension are to be grain size-specific, with exactly the same relations used for sand and gravel The goals of the modelling exercise are a) to develop a model of downstream fining of sand and gravel in which both are treated in exactly the same way, and b) to see if the interplay between sand and gravel can spontaneously give rise to a relatively sharp transition from gravel to sand.

キーワード：rivers、sand、gravel、downstream fining
Keywords: rivers, sand, gravel, downstream fining

Laboratory experiments to predict evolution of sediment size distributions by abrasion and fragmentation in transport

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Sediment particles carry information about the hillslope settings where they are created and the fluvial environments they traverse on their journey through the channel network to depositional zones. Information about upstream tectonic, climatic, geologic, and geomorphic conditions are encoded in the distributions of particle sizes, shapes, and rock types, and in the degree of chemical weathering. However, some information is lost due to abrasion and fragmentation of particles in transport. These processes reduce the size and alter the shape of individual particles, and thus transform the distributions of particle attributes. Despite the importance of particle wear in modulating the signals of upstream conditions contained in sedimentary deposits, many fundamental knowledge gaps remain. Here I report the results of a suite of laboratory experiments designed to enable prediction of particle wear rates, and shape evolution, in specific field settings, based on knowledge of rock strength, rates of energy expenditure in transport, and the initial particle size distribution. Facilities and methods include a set of 4 rotating drums, ranging in size from 0.2 to 4.0 meter diameter, vertically-oriented abrasion mills, and free-fall particle drops. Rock strength was measured by the Brazilian tensile splitting test, and particle shape and angularity were quantified from photographs. Particle size distributions were measured by weighing individual clasts and by sieving. Experiments reveal that abrasion rates scale with the inverse square of rock tensile strength, where strength varies with rock type and with degree of chemical weathering within a single rock type. Wear rates are not substantially influenced by the presence of particles of differing strength, contrary to a commonly-held assumption. Production rate of fine particles (<2 mm) in the drum experiments scales as a power function of the rate of energy expenditure, a result that can be used to extrapolate to field settings where intensity of particle motion can be estimated. Wear rates decline as particles become less angular, at rates that correlate with cumulative travel distance and mass loss. This result enables estimation of both initial particle size and distance from source using measurements of particle angularity and rock strength, but only for particles that have not yet reached a stable surface morphology. Fragmentation during high energy collisions can reset particle angularity, and by creating new coarse particles (>2mm), can transform particle size distributions. Particle drop experiments quantify how fragmentation probability varies with impact energy for a given rock type. Fragment sizes collapse to a single non-dimensional particle size distribution. I illustrate how these experimental results can be used in field settings to distinguish the effects of particle wear from size-selective transport in downstream fining of river bed material, and to infer the initial size of sediments supplied to channels by upstream hillslopes.

Keywords: Sediment, Abrasion, Fragmentation, Experiment, Particle Size Distribution

Simulations of Lateral Erosion in a Mixed Bedrock-Alluvial Meander

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1. Introduction
Most of the previous bedrock channel evolution models use shear stress or stream power of water flow as the deciding factor for lateral erosion. These models use shear stress/stream power erosion rule, and compose all relevant erosional processes into a single hydraulic parameter. These models ignored the effects of sediment transport in the channel. Some recent experiments and field studies have proposed sediment particle impact wear as an overriding factor for bedrock bank erosion (e.g., Fuller et al., 2016). Here, we implemented erosion model of bedrock bank into 2D physics-based morphodynamics model and reproduced the laboratory experiment results.
2. Methodology
2.1 Flume experiment
A laboratory scale experiment was carried out to inspect the interaction between sediment and banks of a bedrock channel. We used a Sine Generated Curve Shaped flume. The flume majorly consisted of weak erodible mortar. The length of the flume was 3 meters and width was 5 cm. The banks of flume were 10 cm high. The bed was covered initially with sediment. The initial alluvial thickness for bed was 0.5 cm. The grain size is 0.75 mm. The sediment used as an alluvial cover for bed was the same size as the sediment supplied as load. Flow discharge, channel slope, sediment feed rate, and grain size were kept constant throughout the experiment. The experiment was conducted for 4 hours.
2.2 Model
The governing equations for flow field and bed deformation in a mixed alluvial-bedrock channel are based on the numerical model proposed by Inoue et al (2016). In this study, we assumed that the lateral erosion rate in bedrock depends on a product of abrasion coefficient of bank with lateral bedload transport rate. We implemented the equations for bedrock bank erosion in the numerical model.
3. Results and Conclusions
In our experiment, the bank erosion occurred predominantly due to bed load abrasion. This shows that sediment supply can be one of the dominant factors causing lateral erosion in bedrock meander. In our experiment, the outer bank was eroded, but the inner bank was not eroded even if the sediment moved near the inner bank.
We compared the bank erosion width in left and right banks of simulation results with laboratory results. We found that our model could quantitatively reproduce the results. Our model could trace the bank erosion, and mimic the behavior of erosion in left and right banks.
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キーワード：岩盤河川、蛇行、室内実験、数値計算

Keywords: bedrock river, meander, laboratory experiment, numerical simulation

Experimental study of upper regime bedforms and the associated modes of bedload transport.

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Upper regime bedforms are important to the interpretation of the stratigraphic record and the study of river floods, coastal storms and turbidity currents but how they form remains poorly defined. Two different upper plane bed configurations are described in the literature, one with long wavelength, small amplitude downstream migrating bedforms, the other with nearly flat beds under a transport layer of colliding grains few tens of grain diameters thick –the sheet flow layer. We performed laboratory experiments to study the interactions between flow hydrodynamics, mode of bedload transport and bedform geometry of the emplaced deposit in these upper regime plane bed configurations. The experiments showed that in the absence of suspended load two upper plane bed configurations exist for increasing values of the bed material transport capacity. The upper plane bed with long wavelength and small amplitude bedforms occurs for a relatively small bed material transport capacity. As the bed material transport capacity increases, downstream migrating antidunes form as a stable bed configuration. Further increasing the bed material transport capacity, the bed flattens out and the sheet flow layer forms. This change in bed configuration is associated with a change in the mode of bedload transport, from *standard bedload transport* with a two-three grain diameter thick bedload layer to *bedload transport in sheet flow mode*, and flow resistances.

Keywords: upper regime plane bed , bedload transport , donwstrem migrating antidunes, sheet flow

The role of saltwater in constructing continental shelves with seaward-migrating clinoforms

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Continental shelves have been generally interpreted as drowned ancient coastal plains developed at low stand. This implies that subaqueous hydrodynamics, sediment transport, and associated morphodynamic process do not contribute the formation and development of currently observed continental shelves. However, recent measurements of submarine sediment processes and sequence stratigraphy of continental shelves have indicated that even at the present Holocene sea level high stand, some shelves or protoshelves with seaward-migrating clinoforms have been developing by the result of long-term fluvial input of suspended sediment/mud and subsequent subaqueous morphodynamic process. Here, we show a description of this physical process of continental shelf formation using a numerical model. More specifically, we demonstrate 1) the role of saltwater in the formation of continental shelves, and 2) long-term development of shelf morphology with seaward-migrating clinoforms associated with interactions among fluvial suspended sediment supply, sediment deposition from hypopycnal plumes, and wave-induced sediment re-distribution on the shelf.

Fluvially derived suspended sediment/mud input is the main source of material for constructing continental shelves. However, in general, we do not see similar bench-like morphologies in old terrestrial lakes which are known to have been influenced by large amounts of fluvial sediment supply. An important factor which differentiates these two environments is dissolved salt in ambient water. In oceans, ambient salt water is generally much heavier than the input sediment-laden water, causing surface plumes (hypopycnal flows). In contrast, ambient fresh water in lakes allows the inflow sediment-laden water plunge directly into the bottom, forming hyperpycnal flows. We numerically model these physical processes to see the differences in the morphodynamic processes between hyper- and hypopycnal flows. The model presented herein is a vertical 2D Reynolds-averaged Navier-Stokes model with the Boussinesq approximation for density-driven flows. It described the effects of both dissolved salt and suspended sediment. The numerical results clearly show that hyperpycnal flows cause less proximal deposition of sediment on the shelf, transporting the sediment into deep water. Conversely, hypopycnal flows greatly contribute to proximal sediment deposition on the shelf. This result indicates that the dissolved salt plays an important role in controlling sediment dispersal, and in particular suppressing direct delivery to deep water.

Another important mechanism for subaqueous morphodynamic process considered here is wave effects for resuspension of sediment deposited on shelves. Long-term sediment supply from hypopycnal flows constructs a large shelf-like morphology, and the height of the shelf eventually builds to wave base. The wave-induced bottom shear stress can then contribute to the resuspension of deposited sediment on the shelf, redistributing the sediment from the shelf to continental slope. We incorporate a simple model to add the effect of bottom shear stress generated by waves into the numerical model. We then consider a scenario which is likely in the natural environment, namely, repeated cycles of short-term fluvial sediment input due to major flood events and the long-term effect of waves due to repeated storm events. The numerical results show that the sediment deposited on the shelf derives from sediment supply from hypopycnal plumes. This sediment is re-suspended by the wave effect, and then wave-supported turbidity currents transports the sediment onto the continental slope. These processes maintain a specific depth on the shelf and generate a seaward-migrating clinoform characterizing the seaward extension of the continental shelf by subaqueous processes.

キーワード：大陸棚、クライノフォーム、溶解塩、波浪作用限界深度、密度流
Keywords: continental shelves, clinoforms, dissolved salt, wave base, density current

Formation of Ilsands on Deltas from Radially Symmetric Flow Expansion

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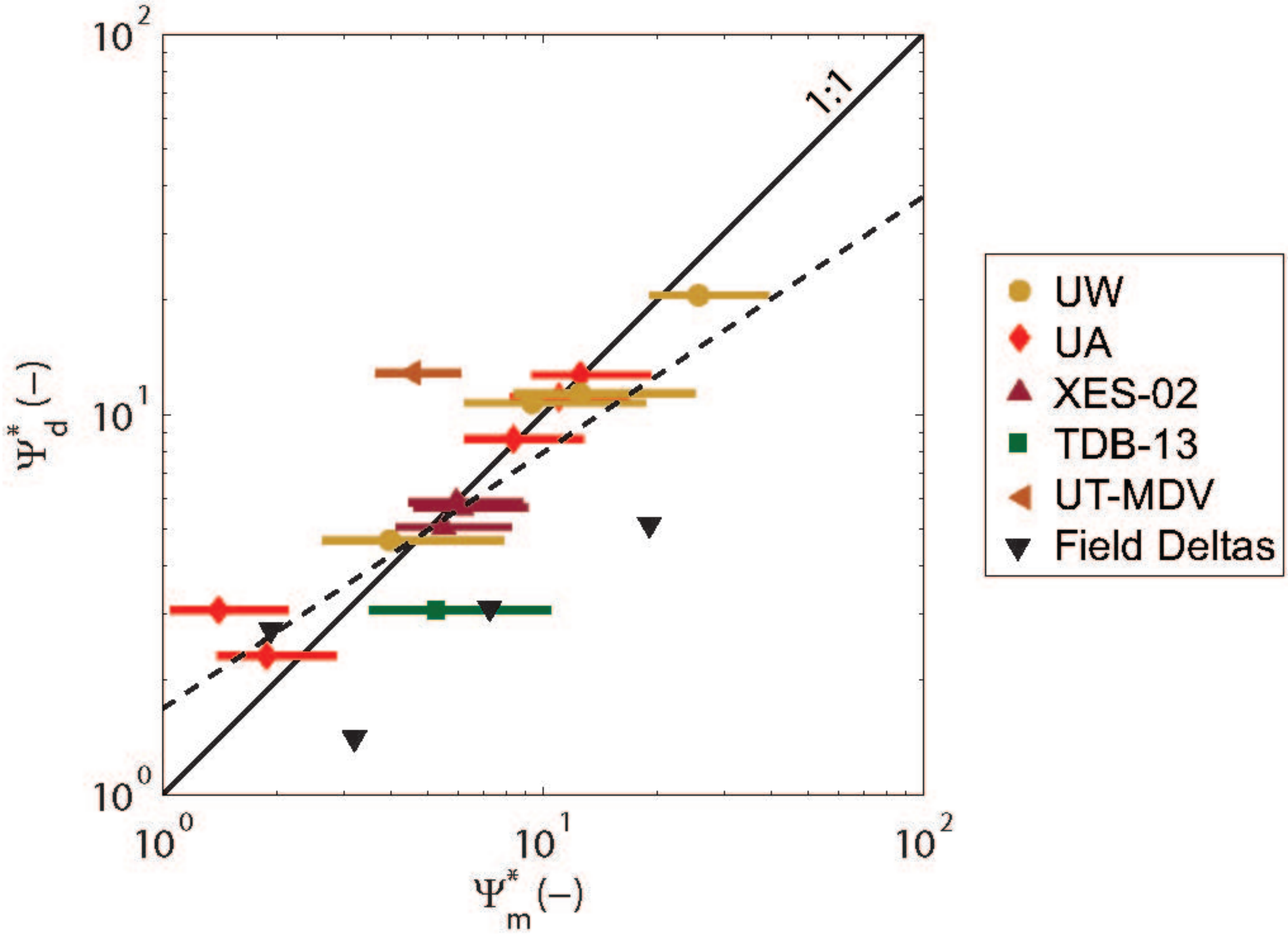
The creation of islands on delta tops is a primary means of coastal land generation and a critical process for interpreting the stratigraphy of ancient deltas. To-date, models of island creation have been largely based in sediment laden jet-theory and its application to river mouths. Inspired by a suite of laboratory experiments and collection of planform data from modern deltas, we propose another model for island formation that is based on topographic flow expansion. Consistent behaviour was observed in 9 new and 5 previously published delta experiments that began as wall-bounded, planar turbulent jets. Initial deposition occurred as predicted by jet theory produced elongate deposits followed by lunate bars. The lunate bars did not immediately evolve into islands. Instead the lunate bars first transitioned into topographic flow expansions that were stable to topographic perturbations. These deposits prograded and maintained a uniform, characteristic flow depth until island formation and channel bifurcation occurred. The islands appeared to form at a consistent distance from the center of the spreading flow. The experimental deltas all developed radially symmetric deposits and flow patterns (i.e. where flow width increases uniformly with radius). We hypothesize that the islands on these deltas form at the distance from the center of spreading, Ψ_m, where flow per unit width drops below that which provides critical stress to move the median grain size. To test this hypothesis, we analyzed channelization and island formation for the 14 experiment and 4 field scale deltas gathered from the literature. Distances to the position of channelization, Ψ_d, were measured and compared to predictions of distance, Ψ_m. Experimental and field data are predicted with a root-mean-square error of 17%, and the best-fit model offers only a modest improvement in explanatory power over a 1:1 line model (i.e. $\Psi_d = \Psi_m$). This new model predicts island formation on delta tops where radially symmetric flow patterns develop from sediment-laden jets before prograding until flow conditions drop below the threshold of motion through radial expansion. This model explains well a set of experimental and natural deltas. The model predicts that the distance to the first channel bifurcation scales with water discharge, scales inversely with flow depth over the apron, and scales with the inverse square-root of median grain diameter.

Keywords: delta, bifurcation, island, jet, flow expansion


10^2
10^1
10^0
1:1
Ψ^*_d (–)
Ψ^*_m (–)
UW
UA
XES-02
TDB-13
UT-MDV
Field Deltas

Two mathematical approaches to delta evolution

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For many morphodynamic problems, the Exner equation can be applied in two different ways. In the first approach, a transport law is prescribed, from which the morphology freely evolves. In the simplest case, if the transport rate is assumed proportional to slope, the long profile becomes governed by a diffusion equation. In the second approach, the morphology is constrained, and it is the transport rate that must accommodate the constrained surface evolution. In the simplest case, avalanching at the angle of repose, the constant slope morphology becomes governed by the eikonal equation. Using either approach or a combination of both, it will be shown that various interesting solutions can be derived to problems of delta evolution. These include the infill of finite reservoirs by hyperpycnal inflows, and the progradation of three-dimensional Gilbert deltas. Laboratory and field examples from Taiwan will be used to compare predicted and observed behaviors.

キーワード：delta morphodynamics、diffusion equation、eikonal equation
Keywords: delta morphodynamics, diffusion equation, eikonal equation

Facies Relationships in a Simulated Fan-delta System

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Intrinsic relationships between associated sedimentary facies have been proven to be existed during the depositional process, such as channel-mouth bar systems in deltaic settings. However, little attention has been paid to the developmental patterns of such associated sand bodies, i.e., channel, mouth bar, and slide-slump deposit, which are favorable for the development of high quality hydrocarbon reservoirs if preserved. Therefore, we conducted a flume experiment to simulate a fan-delta under controlled boundary conditions and hope to explain the genesis of these associated sand bodies.

The delta was simulated in a flume. Volume of sediments and flowrate were variables and were strictly controlled. Sediments mixed with the water supply at the sand pool outflowed from the feeder outlet. Meanwhile, the water volume and tectonic setting were kept constant, without tidal or wave interactions.

The experiment showed developmental relationships between different facies. Subaqueous channels are the underwater extension of subaerial braided channels. As water and sediment were fed into the flume, the subaqueous channel was eventually replaced by a mouth bar. During this evolution process, the mouth bar first prograded, followed by accretion, backstepping and widening, with an increasing to decreasing depositional rate, influenced by backwater effect. After the mouth bar emerged, it caused the flow to bifurcate. The two branches would be bifurcated again by subsidiary mouth bars. Nevertheless, several bars might almost simultaneously develop basinward of the outlet if the channel was wide and shallow. Progressive deposition around the bar increased the angle of bifurcation and the original mouth environment evolved into fan-delta plain. It is worth mentioning that sediment failures would form in front of torrential and highly loaded channels.

The conclusions are: 1) the mouth bar first develops progradationally, then aggradationally, retrogradationally and transversely from the initial formation of the subaqueous channel; 2) there are two modes of channel bifurcation, i.e., multi-stage bifurcation by sequentially formed mouth bars and simultaneous bifurcation by arrays mouth bars; 3) slide-slump deposits are more easily formed in flood periods; 4) in the process of fan-delta development, sedimentary slope break is formed, which is favorable for the development of high quality reservoirs.

Keywords: facies relationships, flume experiment, fan-delta system, channel-mouth bar system

The roles of hydrodynamic backwater and relative sea-level rise in setting deltaic avulsion frequency

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Many of the world’s deltas are built through periods of construction of depositional lobes punctuated by lobe-scale avulsions. Deltaic rivers avulse when backwater effects create a locus of deposition in the river that reaches a critical thickness that scales with the channel flow depth. Recent work suggests that relative sea-level rise can play an important role in setting the pace of aggradation and frequency of avulsions within the backwater zone, but the fundamental relationship between avulsion frequency and sea-level change remains unexplored. We address this knowledge gap using an analytical model and a quasi-2D morphodynamic model. In our preliminary simulations, avulsion frequency increases under faster rates of normalized relative sea-level rise, because more sediment is deposited on the topset relative to the foreset and thus less time is required before the channel avulses. This behavior is well-predicted by our analytical solution, at least for low rates of relative sea level rise. At higher rates of relative sea level rise, avulsion frequency becomes more variable because lobes partially drown between avulsions. Results have implications for the sustainable management of modern deltas undergoing relative sea-level rise and for interpreting avulsions in stratigraphic sequences.

Keywords: Deltas, Avulsions, Sea-level rise

The Kinematics and Sedimentary Record of a Self-evolving Continental Slope Fed by a Prograding Shelf Delta

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A key issue with elucidating terrestrial environmental signals from the deep-sea stratigraphic record is the lack of quantitative theory that facilitates: 1) the separation of signals associated with local autogenics and autogenics of the upstream feeder system, and 2) the separation of autogenic signals from tectonic, climate and sea-level signals. We take the first steps towards understanding the kinematics of sedimentation and the resulting stratigraphic record associated with the coevolution of a prograding shelf delta and the down-dip continental slope fed by turbidity currents, using physical experiments. In a 26 hour experiment, we prograded a delta across a flat shelf, under conditions of constant sea-level rise to mimic pseudo subsidence. We analyze patterns of flow and sedimentation from overhead photographs and topographic scans to characterize the kinematic evolution of the slope during the delta’ s approach to the shelf-edge. In this experiment, the shoreline marked the transition between a transport-limited regime and an advection-settling regime in this experiment. The continental slope experienced a gradual roughening of the surface tied to a growth of depositional topography. As the delta migrated towards the shelf-edge, the proximal slope initially exhibited the vertical growth of topography through persistent, laterally discontinuous sedimentation associated with pathways of higher flow velocity (and likely higher sediment concentrations), followed by compensational lateral stacking of lobes characterized by high sedimentation rates downstream of active delta channels. As the upstream feeder channel migrated laterally, or subaqueous flow on the slope was steered around growing topography, sediment rapidly filled in topographic lows, smoothing away topographic roughness through compensational stacking of sediment bodies. Locations farther down-dip of sediment lobes, characterized by low sedimentation rates, continued to exhibit the vertical growth of topography through persistent, laterally discontinuous sedimentation. The paths of higher velocity flow (likely carrying higher sediment concentrations) in these distal locations remained relatively unchanged for the duration of the experiment.
Our results support the hypothesis that the advection length of the modal grain-size in suspension at the transition from transport-limited to advection settling-dominated, represents the length scale that separated compensational and random or persistent stacking of deposits. Compensational stacking only occurred in zones where: 1) local flow paths were influenced by close proximity to the laterally migrating deltaic feeder channel, and/or 2) rapidly growing lobes characterized by high sedimentation rates were capable of steering flow. These sediment lobes were constructed primarily from coarse silt- the modal grain-size in suspension at the shoreline, and developed at distances bracketed by the estimated advection lengths of coarse silt. Downstream of sediment lobes, temporally persistent and laterally discontinuous sedimentation of finer sediment resulted in the continuous vertical growth of topography. In natural systems, it is likely that distal locations may never enter the “sweet spot” of high sedimentation rates associated with the characteristic advection length suspended sediment, without the influence of allogenic factors.

Keywords: shelf-margins, shelf-edge deltas, stacking patterns, advection length

Stratigraphic feedbacks on free and forced alternate bar morphodynamics

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As rivers aggrade, they develop subsurface stratigraphy consisting of heterogeneous grain-size distributions in the downstream, cross-stream, and vertical directions. During subsequent periods of degradation, grain-size heterogeneity stored in stratigraphy may be exhumed and potentially feedback on the processes that drive morphodynamic evolution. Here we investigate these feedbacks by implementing the ability to store, track, and access bed stratigraphy in the two-dimensional morphodynamic model FaSTMECH. We use a modified active layer approach, in which during aggradation the active layer and bedload are released to and stored in the highest stratigraphy layer. During degradation, the active layer takes on the sediment properties stored in stratigraphy. We simulate two straight-channel scenarios: one with an obstruction at the upstream end to force formation of fixed alternate bars, and one without an upstream obstruction where freely migrating alternate bars can form. Each scenario was modeled with and without stratigraphy enabled to isolate its effect on the system’s dynamics. The simulations with an obstruction showed minimal differences in sediment sorting and bed morphology between runs with and without stratigraphy enabled. However, the free bar simulation with stratigraphy enabled developed bars that were coarser, higher, and wider than the bars from the simulation without stratigraphy. The cyclical periods of aggradation and degradation associated with bar migration result in surface-subsurface interactions producing a corridor of fine bed material connecting the pools, facilitating sediment transport and allowing bars to grow and become coarser. Our results indicate that autogenic stratigraphy can have an important influence on the development and evolution of migrating alternate bars.

Keywords: stratigraphy, morphodynamics, bars

Lost in translation: Defining thresholds for the storage of environmental signals in stratigraphy

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Alluvial basins provide important records of climate and tectonic changes on Earth, as well as information about how land surfaces evolve under different boundary conditions. These deposits also contain important energy and water reserves. Consequently our ability to reliably interpret and predict stratigraphic patterns is fundamentally important both scientifically and in its bearing on broader society. While stratigraphy is our best record of paleo Earth surface dynamics, the record also contains significant gaps over a range of time and space scales. These gaps result from stasis on geomorphic surfaces and erosional events that remove previously deposited sediment. Building on earlier statistical studies, we examine the fidelity of the stratigraphic record in laboratory experiments where the topography of aggrading deltas was monitored at high temporal and spatial scales. The resulting stratigraphic architecture is influenced by both stochastic and deterministic processes. We start by quantifying the temporal scales that climatic perturbations must possess to be stored in stratigraphy via geochemical proxies. Then we investigate the temporal and spatial scales necessary for changes in forcing conditions, including sea level and/or sediment flux, to generate signals in the physical stratigraphic record. Finally, we examine how environmental stochasticity can further complicate signal identification. This work helps improve efforts at recovering meaningful data about autogenic processes from stratigraphic datasets, isolating signals of changing boundary conditions in ancient basins, and modeling and predicting stratigraphy in alluvial basins.

Keywords: Deltas, Stratigraphy, Experiments

マイクロプラスチックの海洋底への拡散と年代決定論
Microplastics: diffusion into ocean floors and methodology for age determination

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海洋でのプラスチック汚染は深刻である．日本海側の海岸に打ち上げられるペットボトルの数々などは，象徴的である．

それらのプラスチックが細かく砕かれたマイクロプラスチックは，世界各地の海洋に拡散し続けている．そして，マイクロプラスチックによって吸着されたPCBなどの有害物質は，海洋生物の体内に吸収，蓄積される．そのような海洋におけるプラスチック汚染の実態は，世界の沿岸において調べられているが，水深数千メートルの深海での影響については未解明である．

一方で，そのような拡散する人工物を用いれば海底堆積物の年代を決めることができる．例えば，有名なものは，セシウム同位体である．セシウム同位体はセシウム134と137とが堆積物の年代決定に用いられる．セシウム134は半減期約2年であり，最近の原発事故や核実験などの指標として用いられ，東北沖での福島第一原発事故以降の堆積作用を調べる上で重要な役割を果たした（例えば，Oguri et al., 2013; Scientific Reportsなど）．セシウム137は，半減期が約30年と長いため，原発事故によって堆積したセシウム137を長い間検出可能であり，堆積物の年代決定の指標として使用されている．セシウム137の検出ピークは，1960年代の核実験，1987年のチェルノブイリ事故とが有名で，海底堆積物の年代指標として使われている．

マイクロプラスチックも同様の人工物であり，塩ビ公表・環境協会によると，日本周辺では1960年代の高度経済成長以降，100万トン/年であったものが，1991年には200万トン/年と，増産が続いている．ただし，昨今の環境問題から，2008年以降は180万トン/年で推移している．それらは腐ることなく，海底に沈積していると予想されるが，その実態は良くわかっていない．

そこで本研究では，水深数千メートルで採取された海底表層のマイクロプラスチックの検出を行い，深海底での新しい年代指標として確立を目指す． また同時に，マイクロプラスチックの海底への拡散経路を調べ，海洋汚染としてのマイクロプラスチックの実態を把握する．

キーワード：堆積年代、マイクロプラスチック、表層堆積物
Keywords: Sediment age, microplastic, Surface sediments

The significant of the sedimentary system in the southwest Ryukyu Trench in terms of Source-to-Sink

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The southwest Ryukyu Trench near Taiwan is an ideal place for source-to-sink studies because the linkage between the terrestrial sediment source of Taiwan and the marine sink in Ryukyu Trench within a short distance can be determined. This study aims to improve our understanding of the oceanic trench sedimentary system. Using bathymetry, seismic reflection data and cored samples in the southwest Ryukyu Trench areas, we determine distinct features of the submarine canyons, trench wedge, bathymetric ridges and fore-arc basins which are linked together to form two sediment dispersal systems. Two sediment dispersal systems can be identified. First, the trench end sediment dispersal system is characterized by the longitudinal sediment dispersal to the southwestern end of Ryukyu Trench via the Hualien Canyon with additional lateral sediment supplies from the Taitung Canyon merging into the lower Hualien Canyon. This system allows Taiwan orogenic sediments transported far-field and to feed sediments longitudinally to the southwest Ryukyu Trench end. This type of longitudinal sediment dispersal demonstrates a link of sediment of land drainage (source) to the far-field deep oceanic trenches (sink) via networks of submarine canyons. Sediments derived from Taiwan orogen mainly transported downslope by submarine canyons are blocked by the Gagua Ridge. Second, the forearc sediment dispersal system consists of the transverse sediment dispersal from the Ryukyu islands down-slope to forearc basins including Hoping, Nanao, East Nanao and Hateruma. Most of the down-slope sediments from Ryukyu islands are blocked by the W-E trending Yaeyama Ridge along the trench slope break and trapped sediments in the forearc basins. The Yaeyama Ridge is considered as a sediment barrier for sediments sourced by the Ryukyu Islands to be transported to the Ryukyu Trench.

キーワード：Sediment transport、Seismic characteristics、Source-to-Sink、Southwest Ryukyu Trench、Taiwan
Keywords: Sediment transport, Seismic characteristics, Source-to-Sink, Southwest Ryukyu Trench, Taiwan

Interaction of forearc basin stratigraphy with growth of accretionary wedge: Insights from numerical simulations

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Forearc basins are important elements along subduction zones; their deposits and structures recorded various events in history at a high resolution. However, forearc basins have received relatively less attention than the deformation front, because their formations depend on complex interactions among uplift/subsidence of backstop, growth/shrink of accretionary wedge, subducting oceanic slab, and covering sediments. It is often difficult to evaluate influence of each factor. In accretion-dominated margins, forearc basins commonly develop on or beside accretionary wedges, indicating growth patterns of the wedge may be primary controllers of the basin formations. Because material fluxes between the boundary of overriding and subducting plates highly influence the wedge growth patterns, They must be also important for development of forearc basins. The aim of this study is to understand formation of forearc basin stratigraphy in terms of sediment fluxes in subduction zones. I performed numerical simulations to reproduce forearc basins formed between growing accretionary wedges and continental backstops. The simulations assumed that sediments filling forearc basin (Q_{inFAB}) were determined by balance among sediment supply to the basin (Q_s), trench fill sediments (Q_{inT}), and subducting sediments from the trench into subduction channel (Q_{outT}). The sediment fluxes of Q_s, Q_{inT}, and Q_{outT} were independently fluctuated, and sediments accreted to the wedge (Q_{inAC}) was Q_s - Q_{inFAB} + Q_{inT} - Q_{outT}. Two models of constant and dynamic taper angles of the wedges were tested. In the dynamic taper model, the taper angle (θ) relied on pore pressure ratios of the wedge interior and the basal detachment, which were functions of Q_{inAC} and Q_{outT}, respectively.

The constant taper models showed positive relationships between Q_{inFAB} with Q_{total} (= Q_s + Q_{inT} −Q_{outT}) or Q_{inAC}. Underfilled basin could exist only when Q_s was smaller than depositional area produced by the wedge growth. At a time of transition from underfill to overfill, trajectories of Q_{inFAB} and Q_{inAC} broke and then returned to the equilibriums with some fluctuations. The dynamic taper models also showed linear relationships between Q_{inFAB} and Q_{total}, although Q_{inAC} and Q_{inFAB} relationships were much more scattered than the constant taper models. A prominent feature of the dynamic taper model was a negative relationship between time-averaged differences of Q_{inAC} and Q_{inFAB}, when θ was increasing or decreasing. The sediment input rates to the basins (Q_{inFAB}) decreased, even though those to the wedge (Q_{inAC}) increased with reducing θ. Similar negative relationships could be observed during increase of θ. These results suggest that growing wedge with changing the taper angle significantly affects the basin stratigraphy. Two end members of the wedge-growth patterns can be considered; (1) progradation by frontal accretion with decreasing θ and (2) vertical growth by basal accretion or thickening by splay faults with increasing θ. For the former type (1), most of Q_{inT} are consumed for progradation of the wedge to approach the reduced θ, resulting in slower sedimentation rate and then occurrence of a condensed section or an unconformity, even though sufficient Q_s is supplied to the basin. The latter type (2) yields more space for sedimentation landward side of the wedge due to uplift of the outer arc high, which leads to faster sedimentation rate or occurrence of an underfilled basin, depending on Q_s.

キーワード：前弧堆積盆、付加体、土砂収支、沈み込み帯
Keywords: forearc basin, accretionary wedge, sediment flux, subduction zone

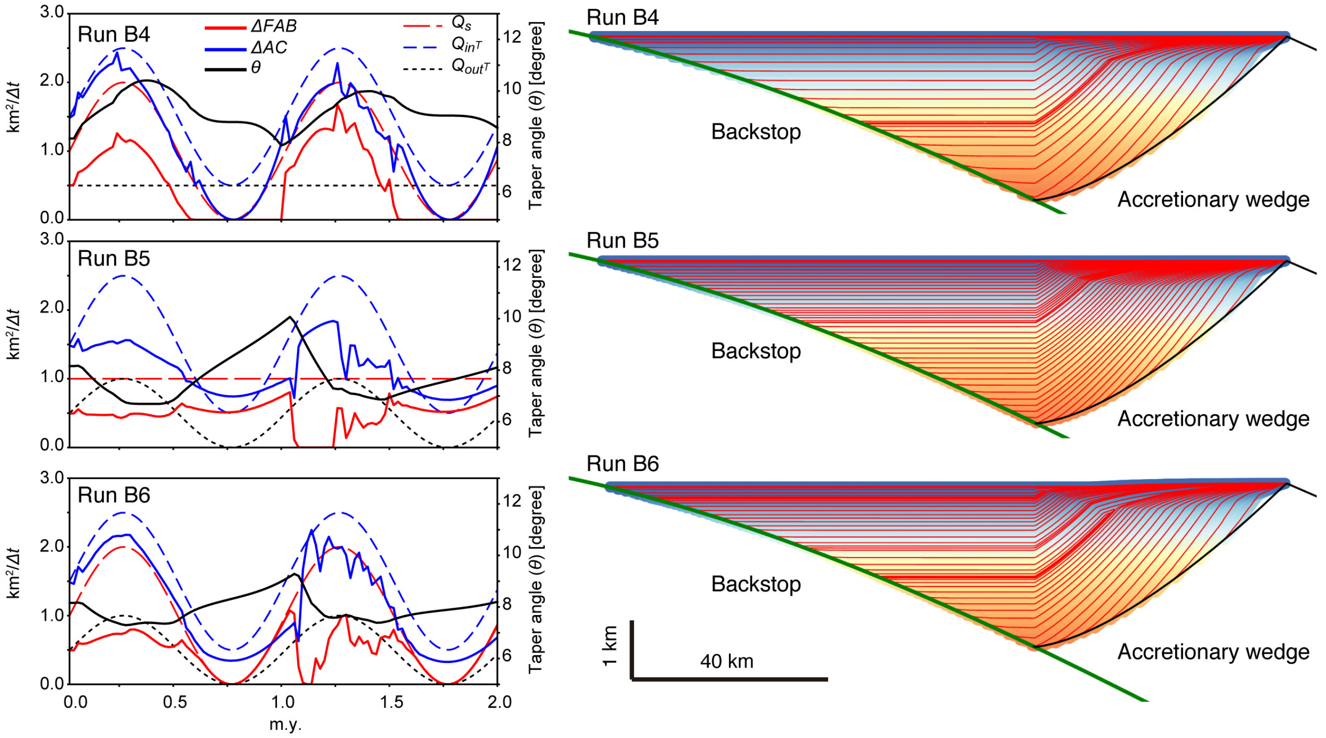

Fig. 1: Selective examples from the dynamic taper models. (Left) Diagrams for initial parameters of Q_s, $Q_{in}{}_T$, and $Q_{out}{}_T$ (see the text for notations), taper angles (θ), and increased areas of forearc basin (ΔFAB) and accretionary wedge (ΔAC) at each time step. (Right) Resultant stratigraphy of forearc basins.

非定常流モデルに基づく津波堆積物の逆解析
Inverse analysis of tsunami deposits using non-steady flow model

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Tsunami deposits provide important clues to understand ancient tsunami events. Here we propose a new inverse model of tsunami deposit emplacement. The model is an improved version of FITTNUSS that is the inversion model proposed by the authors. The model considers both transport of non-uniform suspended load and entrainment of basal sediments, and the flow deceleration process is newly incorporated in this model. This inversion model requires the spatial distribution of deposit thickness and the pattern of grain-size distribution of the tsunami deposit along 1D shoreline-normal transect as input data. It produces as output run-up flow velocity, inundation depth and concentration of suspended sediment. To solve for advection of non-uniform suspended load, a transformed coordinate system is adopted, which increase computational efficiency. Tests of inversion using artificial data successfully allow reconstruction of the original input values, suggesting the effectiveness of our optimization method. We apply our new inversion model to the 2011 Tohoku-Oki Tsunami deposit on Sendai Plain, Japan. The thickness and grain-size distribution of the tsunami deposit was measured along a 4 km long transect normal to the coastline. The result of our inversion fits well with the observations from aerial videos and field surveys. We conclude that this method is suitable for the analysis of ancient tsunami deposits, and that it has the advantage of requiring the minimum information about the condition of the emplacing paleotsunami for reconstruction.

キーワード：津波、津波堆積物、逆解析
Keywords: tsunami, tsunami deposit, inverse analysis

Reconstruction of flow depth and velocity of tsunamis by inverse analysis using thickness and grain-size distribution of tsunami deposits along 1D transect: Application to the 2011 Tohoku-oki tsunami and the 869 Jogan tsunami

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A new inversion model FITTNUSS (Framework of Inversion of Tsunami deposits considering Transport of Non-uniform Unsteady Suspension and Sediment entrainment) was proposed for estimation of tsunami hydrodynamic conditions from characteristic features of tsunami deposits along the transect. The forward model designed for the inverse analysis considers transport of non-uniform suspended load, and deposition from both run-up and stagnant phases of the tsunamis are calculated. The inversion model requires thickness and grain-size distribution of the tsunami deposit along 1D shore-normal transect as input data, and calculates flow depth, flow velocity and concentration of suspended sediments. Here, we applied this inversion model to the modern and the ancient tsunami deposits emplaced in the same region, and compare the reconstructed flow properties for understanding the behavior of the past tsunami. Firstly, the inversion model was applied to the 2011 Tohoku-oki tsunami deposit in the northern part of Sendai Plain. Thickness and grain-size distribution of the tsunami deposit were measured along the 4 km long transect from shoreline to the inundation limit. The run-up flow velocity observed by video footage was 4.2 m/s on average (Hayashi and Koshimura 2013), while the value estimated by the model was 4.15 m/s. The flow depths near shoreline obtained by the field survey and the inverse analysis were 4.9 m and 4.71 m, respectively. Secondly, the inversion model was applied to the 869 Jogan tsunami deposit in the northern part of Sendai Plain. Thickness and grain-size of the tsunami deposit were observed along the 3 km long transect from the paleo-shoreline to the estimated inundation limit. The run-up flow velocity and flow depth were estimated as 6.3-8.8 m/s in average and 5.3-7.8 m near shoreline. Although the 2011 Tohoku-Oki earthquake is often considered as the recurrence of the 869 Jogan Earthquake, the reconstructed values of flow velocity and depth of the 869 Jogan tsunami in the northern part of Sendai Plain were significantly high and deep in comparison with those of the 2011 Tohoku-oki tsunami, suggesting that there could be considerable differences in their generating mechanisms or topographic settings between these two tsunami events.

キーワード：津波堆積物、浸水深、流速、逆解析、2011年東北地方太平洋沖地震津波、869年貞観津波
Keywords: tsunami deposit , flow depth, flow velocity, inverse analysis, 2011 Tohoku-oki tsunami, 869 Jogan tsunami

Controls of Ice Cover on Arctic Delta Morphodynamics and Depositional Processes

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Deltas are dynamic systems that can provide important information on past environmental conditions. Arctic deltas in particular have the potential to preserve critical information about climate change in one of the most temperature-sensitive regions of the Earth. Despite the fact that the responses to climate change in the Arctic can significantly affect deltaic morphology, Arctic deltas have largely been neglected as records of climate conditions, and the mechanism(s) by which ice cover alone produces the resultant delta morphology unique to Arctic deltas remains unexplained. We have performed laboratory experiments to directly evaluate the key controls of ice cover on delta morphodynamics and associated depositional processes to identify signatures of ice cover presence during deposition. Our results show that ice cover drives spatially varying sediment transport on the subaqueous delta clinoform through sub-ice channels, which leads to the development of (1) extended delta lobes built by elongated, subaqueous sediment wedges and (2) highly variable bathymetry with increasing topographic roughness up to a water depth above which bottom-fast ice cover exists. The results of our laboratory experiments provide evidence for the effects of ice cover on delta sediment transport and depositional processes, and predictions for changes to delta morphology in the presence of ice cover during deposition. Notably, the unique seascape features of ice-covered deltas may serve as diagnostic geomorphic markers of cold climate conditions where ice cover exists, and hence, as indicators of climate change captured on Arctic coasts. Therefore, Arctic deltas can potentially be a valuable tool for developing geomorphic models to understand and predict coastal landscape changes in the sensitive Arctic where more rapid and much larger changes (e.g., ice cover, temperature, and sea level) are projected in response to climate change.

Keywords: Arctic deltas, Deltas, Arctic, Climate change, Experimental study

Effect of basin water depth on the morphodynamics of delta distributary channels: A tank experiment

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Recent experimental studies of river deltas have brought a new view that the morphodynamics of distributary channels is seriously affected by basin water depth. In a delta fronting on an extremely deep water, so that the delta cannot prograde, its distributary channels tend to be stabilized in the form of an axial valley and become graded. On the other hand, if the basin water is extremely shallow, the delta’s distributary channels keep autocyclic shifting and are never stabilized. These two extreme examples imply that there exist a spectrum of "intermediates" showing different channel behaviors in response to different basin water depths. The present study challenges to find some characteristic forms of "intermediates" and grasp the whole picture of the spectrum, based on the analytical results of a series of experimental runs that were conducted with different basin water depths of 1 cm, 1.5 cm, 2.67 cm, 4.0 cm and 20 cm, but with the same basement configuration, the same water discharge and the same sediment supply rate. The results of the runs suggest that with moderately deep basin water in front, there can develop a single, quasi-stabilized major channel accompanied by multiple minor channels which are also quasi-stabilized.

キーワード：平衡河川、オートサイクリック、堆積盆水深、チャネルの安定性、デルタ、実験
Keywords: alluvial grade, autocyclic, basin water depth, channel stability, delta , experiment

Analytical and experimental study of dual-slope effects on Gilbert and hyperpycnal deltas over bedrock

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Deltas preserve a vast of sediment prism at the shoreline at different spatiotemporal scales and with diverse environmental settings. The sediment prism subjects to homopycnal (or hypopycnal) flows usually yields a Gilbert-type delta, which has an upward-concaved mild topset, a steep foreset rested at the angle of repose and a relatively flat bottomset. Unlike Gilbert deltas, the sediment prism formed by hyperpycnal flows (or turbidity currents) may yield a delta with its subaqueous foreset upward-concaved and bed slope much milder than the angle of repose. However, our knowledge about the morphodynamics of deltas that prograde over bedrock basements with different subaerial and subaqueous slopes is still lacking. In this study, we investigate the effects of the subaerial and subaqueous basement slopes on Gilbert and hyperpycnal deltas by using analytical and experimental approaches. We propose two newly derived analytical solutions for describing the formation of Gilbert and hyperpycnal deltas over different dual-slope settings, respectively. The exact solutions are quantitatively verified by well-controlled physical experiments, and yield good agreements in both delta profiles and moving trajectories: bedrock-alluvial transition and shoreline. Under constant influx conditions, the scaled delta profiles at different times collapse to a single profile, confirming that the morphological self-similarity would establish over single-slope or dual-slope basements, thus enabling us to use the analytical similarity solutions as a tool for quantifying the relative effects of dual-slope to single-slope basement. Our results reveals that the effects of the subaerial and subaqueous slopes are asymmetric for both Gilbert and hyperpycnal deltas. An increase of the subaerial slope would push the delta forward and upward, leading to an enhanced forward migration of shoreline, a raised yet compressed topset, and a suppressed headward migration of bedrock-alluvial transition. On the contrary, an increase of the subaqueous slope would pull down the delta, suppressing the headward migration of bedrock-alluvial transition, forward migration of shoreline and topset dimensions while increasing the foreset length. Thus, with our analytical framework and in light of the scale independence of delta morphology, our results are likely to apply beyond experimental scales.

Keywords: Gilbert delta, hyperpycnal delta, dual-slope, self-similarity, analytical solution, physical experiment

Bankfull characteristics of alluvial rivers: evolution toward macroscopic equilibrium

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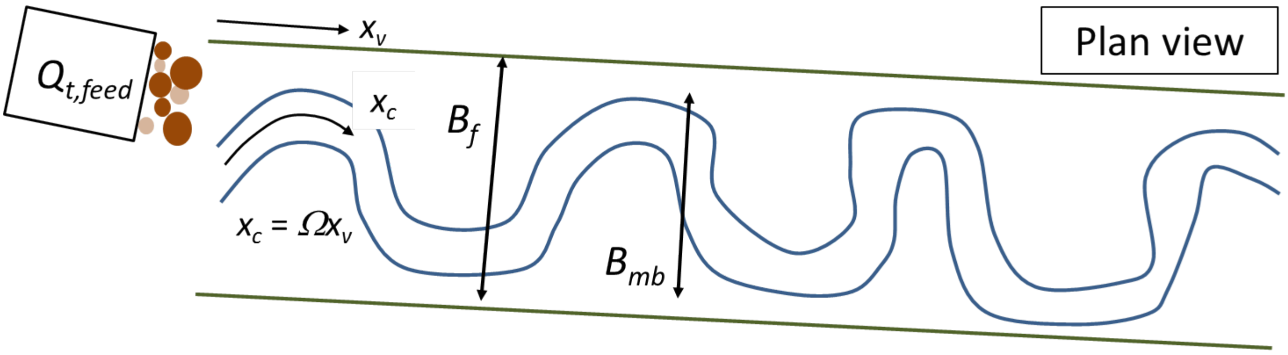
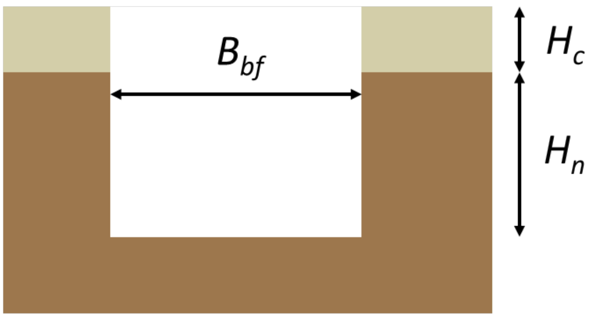
Alluvial rivers are often characterized in terms of their bankfull characteristics (i.e. bankfull discharge, bankfull width, bankfull depth, and channel slope). Studies on bankfull hydraulic geometry relations have shown that bankfull characteristics change in a consistent way with bankfull discharge. This suggests that if bankfull discharge is changed, bankfull geometry should change accordingly. Another problem of interest is the recurrence interval of bankfull discharge, which is often found to be 1 to 2 years. None of these studies, however, reveals what determines bankfull discharge to begin with. As a result, the parameters which determine bankfull characteristics and processes remain unknown. A better understanding of bankfull characteristics would lead to better prediction of how bankfull characteristics change. This knowledge is of great usefulness in many fields including geomorphology, engineering, ecology, and water management. In this study, we propose a framework for the establishment of and evolution to bankfull characteristics of alluvial rivers. It is commonly accepted that an alluvial river should self-evolve toward an equilibrium state, in which the net sediment flux within the reach of interest is zero. Applying this concept, we anticipate that such an equilibrium channel is able to maintain the balance between the fine sediment that is deposited onto the floodplain due to overbank flow (referred as floodplain construction herein) and the fine sediment that is removed from the floodplain throughout lateral channel migration (referred as floodplain destruction herein). Lateral channel migration leads to floodplain destruction because of the average elevation difference prevailing between the (older, thus thicker) outer eroding bank and the (freshly-deposited, thus thinner) inner depositing bank. The equilibrium channel must also be able to transport the supply of bed material without causing overall aggradation or degradation of the reach. In order to quantify floodplain construction and destruction, as well as the bed material sediment transport rate, we use a flow duration. We use this proposed framework to develop a numerical model to find the reach-average equilibrium bankfull characteristics for specified flow duration curve and bed material supply rate. The model not only predicts equilibrium, but can also be used to investigate the adjustment time scale of the system from one equilibrium state to another when it is disturbed. In the model, bankfull width adjustment is accomplished by modeling outer bank erosion and inner bank deposition independently; if outer bank erosion occurs at a faster rate than inner bank deposition, bankfull width increases in time. Bankfull depth adjustment is accomplished by modeling the morphodynamics of fine sediment, which deposits onto the floodplain, and the morphodynamics of bed material. That is, if the incoming bed material discharge is greater than outgoing bed material discharge, the channel bed of the reach in question should increase in elevation, leading to a decrease in bankfull depth. Likewise, if the effect of floodplain construction is greater than that of floodplain destruction, bankfull depth would increase. At the equilibrium state, the reach-averaged rate of outer bank erosion and inner bank deposition are expected to be the same, and the inflowing transport rates of both bed material and fine sediment should be equal to their corresponding outflowing values over a reach of interest. The model is applied to the Minnesota River near Jordan, MN, USA, in order to demonstrate the response of the system to changes in e.g. sediment supply rate and flow duration curve.

Keywords: Bankfull characteristic, Alluvial river, Overbank floodplain deposition, Lateral channel migration



Cross section

$$H_{bf} = H_c + H_n$$



B_{bf}: Bankfull width [L]
B_f: Floodplain width [L]
B_{mb}: Meander belt width [L]
H_{bf}: Bankfull depth [L]
H_c: Upper cohesive layer thickness [L]
H_n: Lower non-cofesive layer thickness [L]
$Q_{t,feed}$: Bed material supply [L^3/T]
Ω: Channel sinuosity [1]

Evaluation of Properties of Bed Phase Transition by the Discriminant Analysis of Experimental and Field Data Sets

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This study provides the quantitative evaluation for modes of the bed-phase transition of bedforms formed by unidirectional flows. Understanding the formative conditions of fluvial bedforms is significant for geological studies, and diagrams showing formative conditions of bedforms have been widely used for analyses of sedimentary structures. However, threshold conditions of bedform formation were not examined quantitatively in previous studies.

In this study, we propose discriminant functions of bedform existence fields in dimensionless parametric space by means of the discriminant analysis using the Mahalanobis distance. We analyzed 3401 existing laboratory and field observation data, and produced new bedform stability diagrams. The discriminant functions of bedform existence fields proposed in this study can be used to evaluate the properties of boundaries between bedform stability fields in terms of error rates of the analysis. Two kinds of the error rates of the discriminant analysis are obtained from (1) ratio of misclassified data and (2) results of cross-validation (the leave-one-out method). For example, as a result of the discriminant analysis, it was indicated that the apparent error rates differ depending on the bedform regimes. The apparent error rates are low at the boundaries between the the lower regime and the transition regime, whereas they are high at the boundaries between the transition regime and the upper regime. The theoretical analysis of Izumi and Parker (2009), which used the weakly non-linear stability analysis of bedforms, might explain the reason why the boundaries between the transition regime and the upper regime are not defined clearly. They predicted that there are hysteresis in the threshold conditions between plane beds and antidunes, and this hysteresis can derive the overlapped region in the laboratory observation data. In this way, our method derives the threshold conditions without any assumptions, providing means for verifying the theoretical examinations.

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キーワード：bedforms、discriminant analysis
Keywords: bedforms, discriminant analysis

The role of grain to grain interactions and turbulence in sediment transport

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Bedload transport impacts sedimentary records as well as channel and delta morphology. Predictions of the onset of sediment motion are notoriously difficult and recent studies have focused on the detailed mechanics of grain movement to improve larger scale sediment flux estimates. In particular, the importance of the duration and magnitude of flow turbulence events that drive grain motion, or the intergranular dynamics that resist sediment movement have been highlighted as being fundamentally important. Despite such recent advances, few studies directly investigate the coupling of these driving and resisting mechanics. Here we use a combination of Discrete Element Method (DEM) modeling and laboratory flume experiments to elucidate the feedbacks between grain to grain interactions and flow turbulence. In the laboratory, we conducted a set of runs in which we measured gravel transport rates for a range of applied shear stresses using a high-speed video (250 frame/s) taken from above the flume. Spectral analysis of the bedload transport time series revealed that sediment movement did not follow the well-known turbulence energy cascade and in some cases scaling between power spectral density and frequency was absent. Such a lack of scaling at some frequencies implies that grain to grain interactions are obscuring the signal of turbulence in bedload transport rates, and flow turbulence alone will not adequately describe sediment transport. To further investigate this we conducted a set of DEM model runs in which we placed a test sphere on a bed of other spheres and applied forces to the test sphere to cause its motion. The model tracked sphere positions and velocities, as well as the force chains between any interacting spheres. Between different model runs, we applied three different random sequences of fluctuating forces on the test sphere. The test sphere was immobile for one of the runs despite all applied force distributions having the same mean force and maximum impulse. In this one run, movement did not occur because the sequence of applied forces caused the test sphere to move in a way that altered the intergranular arrangement of the bed. For example, particle rearrangement in this run caused a lower bed porosity that effectively increased the forces resisting test sphere motion that could not be overcome by subsequent applied forces. If we had separately considered the effects of intergranular dynamics or flow turbulence, we would have incorrectly predicted the mobility of the test sphere. Taken together, our laboratory and DEM model results demonstrate that sediment transport calculations must include both of these two effects and in particular, how the applied and resisting forces on grains interact to control motion.

Keywords: Sediment transport, Turbulence, Intergranular friction, Morphology

Experimental Investigation of Vertical Concentration Profile and Entrainment Rates of Mixed Grain-size Particles in Turbidity Currents

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Turbidity currents in the ocean and lakes are driven by excess density originated from suspended sediment. The dynamics of turbidity currents are largely governed by suspended sediment that is entrained from the bed. Therefore, we conducted the flume experiments of turbidity currents in order to obtain better prediction of transport rates of suspended sediment, especially focusing on differences between single and mixed grain-size cases. The vertical profiles of velocity and sediment concentration of turbidity currents containing mixed grain-size particles are the first subject of this research, which is one of the key parameters in morphodynamic models of turbidity currents. Also, a key feature for the prediction of suspended load is the description of the entrainment rate of basal sediment into suspension at the solid-fluid interface, which is the second subject of this research. The lightweight plastic particles were used in our experiments in order to reproduce suspension in relatively small scale flume (4 m long and 15 cm wide). In this research, plastic particles with the gravity of 1.45 were chosen as the model sediment material. As the focus of the experiments reported here was centered on the dynamics of the current body, rather than the head, care was taken to measure only after the current front had passed and the flow had achieved a quasi-equilibrium state.
Firstly, we report vertical profile of concentration of mixed grain-size sediments in experimental turbidity currents. For the experiments using uniform and nonuniform sediment, the vertical profiles suggested that the distribution of concentration of finer particles is less stratified than the coarser particles, and finer particles have more capability to diffuse upward, which tends to approximately uniform distribution above a certain height. Comparing to the result of Sequeiros et al. (2010), the vertical profiles of dimensionless distribution of suspension concentration shows no significant difference between uniform and mixed-grain sediments, which represented the vertical profiles of concentration of particles have identical assessment between turbidity currents and dense saline underflows.
Secondly, we examined the entrainment rate of basal sediment to suspension in turbidity currents, and compared our measurements with the prediction using the empirical formulation proposed by Garcia and Parker (1991, 1993). In the uniform particle experiments, the prediction of entrainment of sediment is consistent with the measurement accurately, whereas in the mixed grain-size particle experiments, it represent less consistent to anticipation. This implies that the new empirical formulation is needed for predicting entrainment rate of the mixed grain-size sediments into suspended load.

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キーワード：水槽実験、混合流径、垂直方向濃度分布、連行率
Keywords: flume experiment, mixed grain-size particles, vertical concentrantion profile, entrainment rate

Preservation of transient flow conditions in wave ripple defects

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Symmetric sand ripples formed by shallow water waves are one of the most commonly observed patterns in modern environments and in sedimentary rocks. Because the size and spacing of oscillatory flow sand ripples scale with wave conditions and water depth, ripples preserved in sedimentary rocks are important paleoenvironmental indicators used to infer ancient wave conditions. Previous studies of oscillatory flow bedforms have focused on the development of ripple fields under constant wave forcing or on the transient adjustment of one-dimensional wave ripple profiles to changing flow conditions. However, modern and ancient ripple fields often contain bifurcating ridge crests, short secondary crests formed within major ripple troughs, and other two-dimensional defects -- deviations from straight, evenly spaced ripples. Understanding the formation and evolution of these ripple defects could provide insight to transient wave conditions.

We performed a series of experiments in a field-scale laboratory wave tank to characterize the response of a rippled bed to changes in oscillatory flow. In each experiment, we subjected a level sand bed seeded with small perturbations to constant wave forcing to establish an equilibrium ripple field. We then imposed an abrupt change in wave conditions that would produce a different ripple spacing. Taking shadows in time-lapse images as a proxy for bed elevation, we computed the two-dimensional Fourier power spectrum of the sand bed over the course of each experiment to determine ripple spacing and spectral entropy, a measure of the variability of ripple crest orientation and spacing. We also made qualitative observations of dominant defect types over time. Ripples formed from the initially planar bed were straight crested, evenly spaced, and largely devoid of ripple defects. After wave conditions changed, the ripple bed developed unevenly spaced crests with a variety of defect geometries.

Different types of defects developed to accommodate increases in ripple spacing and decreases in ripple spacing, and some defect types emerged only to accommodate a particular magnitude of change in spacing. In experiments with increases in ripple spacing, cup-like depressions formed on ripple crests and propagated outward to divide existing crests in two and increase ripple spacing. In experiments with minor decreases in ripple spacing, ridge crests became hourglass-shaped, and secondary crests formed within widened trough segments. These secondary crests eventually merged with sinuous or fragmented crests to decrease ripple spacing. In experiments with larger decreases in ripple spacing, secondary crests formed parallel to existing ripple crests then migrated laterally towards the trough to decrease ripple spacing. In some experiments with only small increases or decreases in ripple spacing, defects did not form and the ripple field adjusted by lateral migration of unbroken ripple crests.

As ripple fields reached a new equilibrium spacing, the abundance of defects declined and ripple crests became straighter and more evenly spaced. Yet, some defect types persisted even after the ripple bed attained an average spacing equilibrated to new wave conditions. Crest terminations and tuning fork-shaped bifurcations in ripple crests became the dominant defect type after the main adjustment of ripple fields to either an increase or decrease in spacing. These defects propagated across the bed in the direction of the flow as edge dislocations until the end of our experiments.

Based on these observations, we constructed a regime diagram relating specific ripple defect geometries quantitatively to the sign and magnitude change in ripple spacing and the cumulative sediment transport following the change in wave conditions. These results provide a basis for interpreting different defect types and deciphering the magnitudes and timescales of changing water flow preserved in modern coastal environments and the rock record.

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