Modeling of submarine cyclic steps: Controls on their formation, migration, and architecture

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ABSTRACT

Submarine cyclic steps are a newly recognized manifestation of fundamental morphodynamic instability of Froude-supercritical flow over an erodible bed. There is a growing recognition of the global presence and importance of cyclic steps. An attempt was made here to: (1) outline submarine cyclic steps in the context of the sediment waves of various origins; (2) elucidate the physics and key parameters governing their formation, migration, and architecture; and (3) summarize selected numerical experiments on net-depositional and net-erosional cyclic steps in a useful form. The paper also addresses frequent terminology confusion between net-depositional cyclic steps and sediment waves in general.

WHICH SEDIMENT WAVES ARE SUBMARINE CYCLIC STEPS?

Migrating sediment waves constitute the most common bedform on the seafloor (Peckall et al., 2000). In the course of the past 30 years, fields of various types of sediment waves have been observed and described by several authors throughout the world (Fox et al., 1968; Bouma and Treadwell, 1975; Jacobi et al., 1975; Embley and Langseth, 1977; Normark et al., 1980; McCave and Tucholke, 1986; Flood and Shor, 1988; Carter et al., 1990; Howe, 1996; Migeon et al., 2000; Correggiari et al., 2001; Lee et al., 2002; Wynn and Stow, 2002; Fildani and Normark, 2004). Such bed undulations have been found in a wide variety of submarine settings (Fig. 1), including back slopes of channel levees (Piper and Savoye, 1993; Gardner et al., 1996; Nakajima et al., 1998; Normark et al., 2002; Fildani et al., 2006), sides of sedimentary ridges (Embley and Langseth, 1977; Migeon et al., 2001), continental slopes and rises (Jacobi et al., 1975; Kolla et al., 1980; Wynn et al., 2000; Ercilla et al., 2002), thalwegs of submarine channels (Fildani et al., 2006; Smith et al., 2007; Lamb et al., 2008), preexisting debris flow deposits (Howe, 1996), floors of fjords (Bornhold and Prior, 1990), and seaward walls of deep-sea trenches (Damuth, 1979). Sediment waves vary in scale, with wavelengths typically ranging from 0.2 to 7 km and amplitudes from 10 up to 100 m (Migeon et al., 2000). They also vary in composition, from mudwaves observed on the levees of the modern Toyama Deep-Sea Channel in the central Japan Sea (Nakajima et al., 1998), through sand waves recorded along the axis of the Monterey Canyon, California (Smith et al., 2007), to large gravel waves found within the Var Submarine Channel off the Mediterranean coast of France (Piper and Savoye, 1993). Some sediment waves display upslope and upcurrent migration, while others prograde downslope and downcurrent (Migeon et al., 2000).

The appeal of this topic is related to the current production of hydrocarbons from sediment-wave deposits as well as to the interpretation problems facing geologists and other scientists who analyze seismic-reflection records that contain these features. The origin of sediment waves has been mainly attributed to (1) slump compression waves or soft-sediment sliding (Ballard, 1966; Gardner et al., 1999); (2) primary deposition from geostrophic bottom currents (contour currents) (Flood and Shor, 1988; Howe, 1996); or (3) primary deposition from turbidity currents (Damuth, 1979; Normark et al., 1980). The scientific community is still divided on the origin of some of these bed undulations. For example, Lee et al. (2002) suggested that several features previously reported as submarine-landslide deposits may, in fact, be migrating sediment-wave fields, including the “Humboldt slide” on the Eel River margin in northern California, the continental slope in the Gulf of Cadiz, the Adriatic shelf, and the continental shelf off the Malaspinosa Glacier in the Gulf of Alaska. Some other examples of deposits that are being reconsidered as sediment waves generated by density currents are sedimentary structures offshore Ortona in the Adriatic Sea (Berndt et al., 2006) and the Llobregat prodelta (Urgel et al., 2007).

Fine-grained sediment waves (mudwaves) emplaced by contour currents and turbidity currents display similar morphology, and it is often hard to distinguish between the two. In some cases, these waves are built by the complex interaction of both contour currents and turbidity currents, as demonstrated by Howe (1996), who studied two fields of sediment waves located in the Rookall Trough (North Atlantic Ocean).

The main criteria for distinction between mudwaves formed by turbidity currents and those formed by contour currents are the orientation of crests, the direction of migration, and their association with channels. Turbiditic mudwaves have crests parallel or subparallel to both channel margins and topographic contours (Embley and Langseth, 1977; Normark et al., 1980; McHugh and Ryan, 2000). They have been proposed to migrate upslope toward the current source, thus resembling antidunes (Embley and Langseth, 1977; Normark et al., 1980). In contrast, mudwaves emplaced by contour currents tend to have crests oblique to topographic contours and current direction (Embley and Langseth, 1977; Flood et al., 1993). They generally migrate at an angle clockwise to the current flow in the Northern Hemisphere (Blumensack and Weatherly, 1989; Flood et al., 1993), and have no genetic relation to channel environments.

Two simplified hydraulic models have been used to analyze flow conditions that lead to mudwave formation: an antidune model for sediment waves of turbiditic origin, and a lee-wave model for mudwaves due to contour currents. The former proposes that the sediment waves develop below in-phase waves generated by a Froude-supercritical turbidity current, 

\[ F_{tu} > 1 \]

(Normark et al., 1980; Wynn et al., 2000). The latter proposes that internal waves (lee waves) are generated in a weakly stratified near-bottom environment.
flow as it passes over the sinusoidal topography consisting of mudwaves (Flood, 1988; Blum-sack and Weatherly, 1989).

Most of our knowledge of the formation and development of sediment waves generated by contour currents comes from the evidence collected under the project MUDWAVES in the Argentine Basin (Flood et al., 1993; Manley and Flood, 1993; Weatherly, 1993). The project demonstrated that the lee-wave model could be successfully applied in the field to explain the waves made of fine-grained cohesive sediment (mudwaves) that are transported in suspension by contour currents and display no traction effect.

 Apparently, the vast majority of sediment waves in the ocean are of turbiditic origin. Several authors have reported on the characteristics of various sediment-wave fields generated by turbidity currents (Damuth, 1979; Bornhold and Prior, 1990; Gardner et al., 1996; Wynn et al., 2000). The focus of this paper is on submarine cyclic steps and to some extent on downstream migrating antidunes. Submarine cyclic steps constitute a class of large-scale, upstream-migrating turbiditic sediment waves formed predominantly by suspended load transport. Other turbiditic sediment waves that can be resolved in acoustic and seismic seafloor images are antidunes. In addition to these large-scale waves attributed to supercritical flows, there are different kinds of migrating turbiditic bedforms that are detected at subresolution scale in outcrops and cores. These lower-amplitude asymmetrical bedforms, created by subcritical flows, include ripples (e.g., Reineck and Singh, 1975) and dunes (e.g., Mohrig et al., 2001). For want of a better word, they are classified here as “ripples/dunes” and are not elaborated further.

**SUBMARINE CYCLIC STEPS: NEW MANIFESTATION OF A RECOGNIZED CLASS OF BEDFORMS**

Submarine cyclic steps had not been recognized until recently, when numerical results of Kostic and Parker (2006) and consequently Fildani et al. (2006) revealed that in many cases turbiditic sediment waves may represent yet another manifestation of fundamental morphodynamic instability of Froude-supercritical flow over an erodible bed. Rhythmic bedforms in the ocean associated with this instability seem to be in the same class as similar bedforms observed in open-channel flows, that Parker (1996) has named “cyclic steps.” They are also referred to as “chutes and pools” (e.g., Vanoni, 2006), since a shallow and swift Froude-supercritical flow in the chute transitions into a deep, slow-moving Froude-subcritical flow in the pool, through a hydraulic jump, as illustrated in Fig. 2A. Fluvial cyclic steps have been observed and explained in a variety of subaerial settings, including transportational cyclic steps in alluvium (Winterwerp et al., 1992; Taki and Parker, 2005), erosional cyclic steps in bedrock streams (Koyama and Ikeda, 1998; Wohl, 2000; Sklar and Dietrich, 2004), and erosional cyclic steps incised into a cohesive bed (Parker...
and Izumi, 2000). More details on subaerial manifestations of cyclic steps can be found in Kostic et al. (2010).

The relevant Froude number in river flows is $Fr = U/\sqrt{gh}$, where $h$ denotes the flow depth, $U$ denotes the depth-averaged flow velocity, and $g$ is the gravitational acceleration. Its submarine counterpart applicable to all buoyancy-induced flows, including turbidity currents, is the densimetric Froude number $Fr_d = U/\sqrt{gRCh}$, where $h$ is an appropriate measure of the turbidity current thickness, $U$ denotes the depth-averaged turbidity current velocity, $C$ denotes the depth-averaged volumetric concentration of suspended sediment, and $R$ is the submerged specific gravity of sediment.

Submarine cyclic steps consist of coherent trains of upstream-migrating steps, bounded by internal hydraulic jumps. Each step can be divided by a point where $Fr_d = 1$ into an upstream subcritical zone ($Fr_d < 1$) and a downstream supercritical zone ($Fr_d > 1$), as shown in Fig. 2B. The subcritical flow induces net sediment deposition through enhanced deposition/suppressed incision, while the supercritical flow induces net sediment erosion through suppressed deposition/enhanced incision. The presence of internal hydraulic jumps at either end of each step stabilizes the morphodynamics of the flow, so that the entire train displays an orderly upstream migration.

**SUBMARINE CYCLIC STEPS OR ANTI-DUNES: RATIONALE BEHIND THE CONFUSION**

It is of value to mention here that, within an appropriate range, a steady, uniform Froude-supercritical flow running over a plane erodible bed can give rise to a spontaneous evolution of a seabed into antidunes rather than cyclic steps. Antidunes are the bed undulations for which the interface is in phase with the flow boundary layer (Kennedy, 1963). They can migrate either upstream or downstream (Engelund, 1970; Fredsoe, 1974; Carling and Shvidchenko, 2002). Downstream-migrating antidunes are rather rare, and they tend to be asymmetrical, with a steep lee face similar to dunes. Recent experiments of Spinewine et al. (2009) on deep-sea sedimentary wedges provide evidence for the formation of downstream-migrating antidunes formed predominantly by bedload transport. These bedforms appear to be analogous to those observed along the thalwegs of some steep submarine channels (Piper and Savoye, 1993). They are not discussed herein.

Upstream-migrating antidunes are perhaps the most common bedforms of Froude-supercritical flows and tend to be symmetrical. Until recently, submarine sediment waves associated with turbidity currents had typically been characterized as antidunes or antidune-like features (Kubo and Nakajima, 2002; Normark et al., 2002; Lee et al., 2002), largely because they migrate up-slope as the depositional surface accretes. The numerical experiments on internal hydraulic jumps and associated depositional signatures (Kostic and Parker, 2006) have indicated that in many cases such sediment waves represent yet another manifestation of cyclic steps, rather than antidunes. The large-scale deposits and scourings generated by complex non-antidune submarine underflows are termed here “submarine cyclic steps.” Fildani et al. (2006) and Lamb et al. (2008) have provided additional field-scale evidence on these ubiquitous features in the ocean.

Submarine cyclic steps and upstream-migrating antidunes are closely related rhythmic bedforms that share three key features: (1) they march upstream in echelon; (2) they are generated by unstable Froude-supercritical turbidity currents; and (3) they are formed predominantly by suspended load transport. However, they differ in three important ways: (1) cyclic steps are long-wave bedforms, in that the ratio of wavelength to flow thickness is of the order of 10 or larger. Antidunes are short-wave bed undulations, with the same ratio being of the order of 5 or smaller; (2) cyclic steps leave a deposition record that clearly shows a coherent, quasi-permanent train of steps. Antidunes are ephemeral features that rarely ever leave a clear depositional signal—they initiate, form into trains, grow in amplitude, and suddenly break and repeat this process in a different place; (3) cyclic steps are bounded by sustained internal hydraulic jumps that maintain their form. Antidunes emerge in response to Froude-supercritical flows for which the interface is in phase with the bed.

**SLOPE BREAKS THAT GENERATE INTERNAL HYDRAULIC JUMPS AND MOLD CYCLIC STEPS**

The presence of a slope break is a necessary, but not a sufficient condition for the spontaneous evolution of an erodible plane bed into cyclic steps. We will now take a closer look at the physics governing internal hydraulic jumps in turbidity currents.

A slope break associated with a transition from a relatively steep to a relatively mild slope can, under right conditions, cause a turbidity current to undergo a hydraulic jump (Mutti, 1977; Russell and Arnott, 2003; Kostic and Parker, 2006, 2007). Such slope breaks can occur at the canyon-fan transitions, on the back side of submarine levees, at the base of continental slopes and rises, and along channel thalwegs. Consider the governing equations for a steady, gradually varied turbid flow (e.g., Kostic and Parker, 2007) that is free to develop in the streamwise direction of a submarine channel, which displays a slope break (e.g., Fig. 3A):

$$h \frac{dU}{dx} = \frac{s - e}{Fr_d^2 + 1} \left(-c_{f} Fr_d^2 + \frac{1}{2} c_{f} Fr_d^2 + \frac{1}{2} \frac{\nu}{\rho} \left(1 - \frac{U e h}{r g u} \right) \right)$$

(1)
Figure 3. Submarine depositional signals associated with internal hydraulic jumps. (A) Single backward-facing step (trough) along the New Jersey continental slope–upper rise transition (adapted from Pratson et al., 2000). (B) Trains of net-depositional cyclic steps (turbiditic sediment waves) and net-erosional cyclic steps (scour holes) on the outer flank of the Monterey Shepard Meander, California (adapted from Fildani et al., 2006). VE—vertical exaggeration.

\[
\frac{dh}{dx} = -S + e_c \left( 2Fr_d^2 - \frac{1}{2} \right) - S g \frac{1}{2} \left( 1 - \frac{Ue_c h}{r_q} \right) \left( Fr_d^2 - 1 \right) \tag{2}
\]

\[
\frac{dq}{dx} = -r_q \frac{q}{h} \frac{v_s}{U} \left( 1 - \frac{Ue_c h}{r_q} \right) \tag{3}
\]

The dependent variables in the above relations are the current depth \( h \), the flow velocity \( U \), and the volume transport rate of suspended sediment per unit width \( q \). The transport rate \( q \) is a conservative variable defined as \( q = hUC \). Furthermore, \( s \) is a bed-attached streamwise coordinate, \( S \) is the streamwise bed slope, \( c_f \) is the bed friction coefficient, \( r_q \) is a multiplicative constant, \( v_s \) is the fall velocity of sediment, \( e_c \) is the coefficient of water entrainment, and \( e_s \) is the coefficient of entrainment of bed sediment.

For a supercritical turbidity current to display a hydraulic jump, the flow must decelerate from a region where \( Fr_d > 1 \) toward a jump, where \( Fr_d = 1 \). In other words, the velocity \( U \) must decrease monotonically in \( x \), or \( dU/dx < 0 \) in Equation (1). Since the denominator of the right-hand side of (1) is positive for a supercritical flow, the numerator must be negative to render the formation of a hydraulic jump. The first term in the numerator on the right-hand side of (1) represents the driving force of gravity, the second and third term account for the interfacial and bed friction, respectively, while the last term accounts for net deposition of sediment, which is deposition of suspended sediment on the bed minus erosion of bed sediment. The streamwise pull of gravity in (1) and the accelerative force on the flow due to deposition of sediment on the bed suppress the ability of the flow to undergo an internal hydraulic jump. In contrast, bed friction and interfacial friction due to water entrainment, along with the decelerating force on the flow due to entrainment of bed sediment, promote the formation of the jump. In other words, highly erosional turbidity currents regularly undergo internal hydraulic jumps, while highly depositional turbidity currents do not display jumps. The latter remains supercritical and either thicken after the slope break, or die out upstream or downstream of the break due to rapid deposition. An in-depth analysis of the limits on formation of internal hydraulic jumps can be found in Kostic and Parker (2006, 2007).

The case of an open-channel flow can be recovered from Equations (1)–(3) by setting \( e_c = 0 \) and \( v_s = 0 \), which leaves only two forces in the numerator on the right-hand side of (1): gravity and the bottom friction. Thus, a supercritical open-channel flow fails to display a hydraulic jump in response to the slope break only if the mildly sloping reach downstream of the break is not long enough to support the transition from a supercritical to subcritical flow (Kostic and Parker, 2007).

Fig. 3 illustrates how internal hydraulic jumps triggered by different submarine transitions can, under the right conditions, generate distinct bed morphologies (Kostic and Parker, 2006), from a single backward-facing-step sculpted by a single internal hydraulic jump to a coherent, quasi-permanent train of upstream-marching steps molded by multiple hydraulic jumps (i.e., cyclic steps), which are the focus of this paper.

How do internal hydraulic jumps generate step-like depositional signals such as cyclic steps? Several parameters defined below are useful in characterizing the governing physics. The deposition rate of suspended sediment from the flow onto the bed \( D \) and the erosion rate of sediment from the bed into the flow \( E \) are typically evaluated as follows:

\[
D = v_i e_i C \tag{4}
\]

\[
E = v_i e_i \tag{5}
\]

In the “four-equation” formulations (Fukushima et al., 1985; Parker et al., 1986), the shear velocity \( u_s \) is related to the balance of turbulent kinetic energy \( K \), such that

\[
u_s = \alpha K, \tag{6}\]

where \( \alpha \) is a dimensionless coefficient specified algebraically (Parker et al., 1986).

In addition, Kostic and Parker (2006) introduced a drop in the bed Shields number \( \Delta \tau^* \) to quantify the corresponding drop in mobility of bed sediment across the jump, such that

\[
\Delta \tau^* = \left( \frac{\Delta u_s}{v_s} R_f \right)^2, \tag{7}\]

where \( R_f = v_s / \sqrt{\gamma g D} \). \tag{8}\]

Here \( R_f \) denotes a dimensionless particle fall velocity, \( \Delta u_s \) denotes the drop in shear velocity across the jump, and \( D \) is the mean grain size of the sediment.

The transition from a swift supercritical to slow subcritical flow through a hydraulic jump is manifested in terms of a step decrease in kinetic energy and therefore bed Shields stress across the jump. The drop in Shields number leads to a step drop in the erosion rate across the jump due to drop in entrainment of bed sediment. In contrast, the deposition rate of sediment is continu-
ous through the jump due to a continuous profile of suspended sediment concentration. Thus, the resulting depositional signal takes the form of a single or multiple backward-facing steps caused by enhanced net deposition (thickening of the deposit) on the downstream side of the jump(s).

**CONTROLS ON FORMATION OF SUBMARINE CYCLIC STEPS AND THEIR CLASSIFICATION**

Work of Kostic and Parker (2006) resulted in a numerical model that produced submarine cyclic steps for the first time. The model is based on the steady, layer-averaged “four-equation” formulation of Fukushima et al. (1985) and Parker et al. (1986). It encompasses unsteady integral statements of conservation of water mass, downslope momentum, suspended sediment in the underflow, and turbulent kinetic energy, which are fully coupled with the Exner equation of the conservation of bed sediment. A detailed discussion on the numerical model can be found in Kostic and Parker (2006) and Fildani et al. (2006). Therefore, no attempt is made here to outline the model. Rather, the goal of this section is to elucidate the parameters that govern the formation, growth, and migration of cyclic steps.

The results of a dimensionless analysis of Kostic and Parker (2006) are amended here to demonstrate that any parameter $N$ of the depositional signal due to a turbidity current–bed interaction is a function of the following dimensionless parameters:

$$N = f\left( {F_{\text{d},c}, R_s, S_o, C_p, \rho \frac{L_{\text{break}}}{L} \frac{v_s}{U_o} \Delta \tau^*, \tau, C^*} \right) \tag{9}$$

where $F_{\text{d},c}$, $R_s$, and $U_o$ are the inflow values of $F_{\text{d},c}$, $C_p$, and $U$, respectively; $S_o$ is the initial bed slope; $\lambda$ is bed porosity; and $L_{\text{break}}/L$ is a ratio that defines the position of the slope break relative to the length of the analyzed domain. Furthermore, $r_s$ is the multiplicative constant ranging from 1 to 2 (Garcia, 1993), which defines a ratio of the near-bed concentration of suspended sediment to the corresponding layer-averaged value, and $C^*$ is an “equilibrium” coefficient of bed friction as defined by Fukushima et al. (1985). The limited effects of $r_s$ and $C^*$ are not analyzed here.

A dimensionless coefficient $\rho$ of Kostic and Parker (2006) characterizes the ability of bed sediment to resist erosion (called here “availability of sediment for erosion” or “entrainment limiter”). This parameter ranges from 0 to 1 ($p = 0$ for bed rock, and $p = 1$ for completely noncohesive, loose material): it takes into account the observation that deep-marine sediment deposits tend to consist of relatively noncohesive sandy layers interspersed with relatively cohesive muddy layers. Muddy and even sandy bed sediments tend to develop strength over time through consolidation, and so resist erosion by overriding turbidity currents.

The dimensionless parameters $v_s/U_o$ and $\Delta \tau^*$ play an important role in cyclic step formation. The ratio of the sediment fall velocity to inflow velocity $v_s/U_o$ is linked to the cutoff size of sediment that causes turbidity currents to undergo internal hydraulic jumps. Kostic and Parker (2006) established that supercritical turbidity currents driven by sediment fine enough to satisfy the approximate condition $v_s/U_o < 3 \times 10^{-3}$ regularly display an internal hydraulic jump induced by the slope break, while the coarser-grained currents for which the ratio $v_s/U_o > 5 \times 10^{-4}$ do not undergo a transition to subcritical flow due to a rapid rate of sediment deposition on the bed. When a hydraulic jump does occur in response to a slope break, the drop in bed Shields number $\Delta \tau^*$ across the jump can be used to determine whether the jump is strong enough to leave a clear depositional signal in a depositional record. A crude criterion of Kostic and Parker (2006) implies that $\Delta \tau^*$ needs to be greater than three to yield a detectable depositional signal.

The effect of the median grain size of sediment $D$ [given by the dimensionless fall velocity $R_s$ in Equation (9)] and the availability of bed sediment for erosion $p$ has been investigated extensively by Fildani et al. (2006). They applied the numerical model of Kostic and Parker (2006) to study sediment waves and scour holes on the outside levee of the Shepard Meander of the Monterey Channel offshore California. Their work provided strong evidence that these features fall within the rubric of submarine cyclic steps and can be classified as: (1) net-depositional cyclic steps, also called “sediment waves,” that are analogous to the sediment waves on the external levee of the Shepard Meander (Fig. 3B); and (2) net-erosional cyclic steps, also called “scour holes” or “scour depressions,” that are analogous to a linear series of scour-shaped depressions in the Monterey East Channel (Fig. 3B). Since the term “sediment waves” is already widely used to describe all wave-like bedforms of various origins, including these attributed to turbidity currents, “sediment waves” that qualify as net-depositional cyclic steps are called hereafter “turbiditic sediment waves” or net-depositional cyclic steps to avoid any terminology confusion.

By and large, the most common turbiditic sediment waves are those observed on the flanks of submarine channel levees. Such features have been identified in many deep-sea depositional systems around the globe, including the Amazon Fan (Flood et al., 1995), the Zaire Fan (Migeon et al., 2004), the Var Sedimentary Ridge (Migeon et al., 2000, 2001), and the Kramis Sedimentary Ridge (N. Babonneau, 2010, personal commun.). Work of Fildani et al. (2006) suggests that these features are likely to be net-depositional cyclic steps generated by flows stripped off large and thick turbidity currents moving through the main submarine channel. Recent experiments of Spinewine et al. (2009) documented the formation of a train of long upstream-migrating bedforms bounded by internal hydraulic jumps in the laboratory. These features were unambiguously identified as net-depositional cyclic steps.

Cyclic scours observed along thalwegs of some steep canyons and distributary channels created at partial channel avulsions are likely to be net-erosional cyclic steps (Fildani et al., 2006; Lamb et al., 2008; Heinio and Davies, 2009). A narrow corridor of net-erosional cyclic steps in a protochannel may be the initial phase of channel evolution. With feedback between erosion and flow concentration, this process may eventually construct the main conduit extending from the main channel, thus fostering a major avulsion (Fildani et al., 2006; Normark et al., 2009).

In addition to net-depositional and net-erosional cyclic steps, Fildani et al. (2006) also recognized a class of numerical cyclic steps that are neither net-depositional nor net-erosional everywhere.

The numerical experiments presented in Figs. 4 and 5 pertain to overflows onto a levee from the Monterey Channel. The purpose of the experiments was to classify cyclic steps and study the controls on their growth and migration. In order to improve resolution and computational stability at discontinuities, the numerical scheme used in the original model of Kostic and Parker (2006) was replaced here with a high-resolution, oscillation-free central difference numerical scheme of Kurganov and Tadmor (2000). The modeling input parameters were selected as follows: the initial turbidity current depth $H_i = 20$ m, initial velocity $U_o = 3.5$ m/s, initial volume sediment concentration $C_o = 0.01$, and bed porosity $\lambda = 0.5$. The initial three-point profile is loosely based on the present-day down-levee profiles on the outside of the Shepard Meander. The profile consists of a proximal reach with a length of 6 km and slope of 1.3%, followed by the distal reach with a length of 19 km and slope of 0.3%. In the numerical experiments, the flow over the levee is sustained for 192 h to simulate a sequence of repeated, relatively sustained turbidity current events of similar magnitude totaling 192 h of effective flow. The real time between successive...
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During periods of sediment deposition, events may be from weeks to decades, allowing levee deposits to develop strength through consolidation. The results in Fig. 4 document the relative ease with which an initially flat, three-point bed can spontaneously evolve into either net-depositional or net-erosional cyclic steps due to stripped supercritical turbidity currents. The combined effect of the sediment grain size $D$ (or $R_f$ in Equation (9)) and the availability of sediment for erosion $p$ on the character of submarine cyclic steps is apparent. Fig. 4A-1 reveals three complete upstream-migrating turbiditic sediment waves bounded by internal hydraulic jumps (Fig. 4B-1) for an experiment in which the median grain size was set to 80 μm and the entrainment limiter was set to 0.04. Next, a change in flow regime is considered in a way that a stripped turbidity current is expected to focus over time (Izumi, 2004), possibly through a breach in the levee, and become competent to establish net-erosional conditions sufficient to excavate a protochannel. The median grain size was thus reduced to 25 μm, and the entrainment limiter was set to 0.10, which resulted in four scour holes or depressions bounded by internal hydraulic jumps (Figs. 4A-2 and 4B-2). The net-erosional cyclic steps are longer than net-depositional cyclic steps, which is consistent with the Monterey system bedforms (Fildani et al., 2006). The former also migrate upstream, as captured by the numerical model (Fig. 4A-2), even though no internal structure is preserved in the depositional record to demonstrate the migration as seen for the net-depositional cyclic steps.

The numerical experiments in Figs. 5A–5F elucidate the impact of selected control parameters of Equation (9) on the growth and migration of the most common cyclic steps—turbiditic sediment waves. The effect of controls is illustrated by comparing the results of Fig. 4A-1 to those of Figs. 5A–5F, all of which pertain to the same conditions as the experiment in Fig. 4A-1, except for the value of one selected control parameter. For example, the initial slope $S_o$ of the proximal levee reach was increased from 1.3% in Fig. 4A-1 to 2.5% in Fig. 5A to demonstrate that steeper levees yield a cohort of shorter steps, which emerges further downstream. Higher values of the inflow densimetric Froude number $Fr_d$ yield inflows with lower turbulent kinetic energy, thus promoting the formation of hydraulic jumps. For example, when the inflow concentration $C_o$ was increased from 0.01 in Fig. 4A-1 to 0.03 in Fig. 4A-1, the number of internal hydraulic jumps and associated steps amplified. The effect of the inflow densimetric Froude number $Fr_d$ was investigated here by changing the inflow depth from 20 m in Fig. 4A-1 to 100 m in Fig. 5F. Thicker flows tend to generate fewer hydraulic jumps, which in turn mold a train with fewer steps of larger scale.

**CLASSIFICATION OF NET-DEPOSITORIAL CYCLIC STEPS AND IMPLICATIONS FOR A CHANNEL-LEVEE EVOLUTION**

Turbiditic sediment waves can be characterized by three different geometries: symmetrical, asymmetrical, and “inverse” asymmetrical...
sediment waves, as established by Migeon et al. (2000), who studied sediment waves generated by turbidity currents on the Var Sedimentary Ridge in the Ligurian Sea in the northwestern Mediterranean. These wave geometries were investigated numerically herein. The numerical experiments, shown in Figs. 6 and 7, demonstrate for the first time that all three geometries are in point of fact distinct manifestations of net-depositional cyclic steps. The experiments pertain to the seismic profile NIC34 across the eastern part of the Var Ridge and were conducted over the initial bathymetry consisting of a train of asymmetric turbiditic sand waves in Fig. 6. The modeling input parameters were not meant to be precise, but rather to give a plausible picture of the stripped flows that could generate all three geometries. They were selected as follows: the initial velocity $U_0 = 4.0$ m/s, the initial volume sediment concentration $C_o = 0.01$, mean grain size of sand $D = 100 \mu m$, i.e., fine sand, availability of sediment for erosion $p = 0.012$, and the total simulation time $T = 192$ h. The numerical experiment in Fig. 6A, with a 20-m-thick supercritical overflow running over the prescribed levee bathymetry, reveals a train of internal hydraulic jumps that give rise to typical asymmetrical sediment waves associated with the predominance of upslope and upcurrent progradation. In contrast, the experiment in Fig. 6B, with a 50-m-thick overflow demonstrates that thicker turbidity currents tend to generate symmetrical sediment waves. Such geometry results from a more active vertical aggradation than an upslope progradation. If the symmetrical sediment waves drape over the older upstream-marching asymmetric sediment waves, they can gradually fill up the upstream troughs and flanks of older waves to establish
"inverse" asymmetrical sediment waves (Fig. 6B). This "inverse" geometry favors the vertical aggradation, which is sometimes combined with a slight downstream progradation. The entrainment limiter \( p \), which was set equal to 0.012 in Fig. 6B, was increased to 0.03 in Fig. 7 to illustrate that a 50-m-thick overflow can sculpt asymmetrical rather than symmetrical sediment waves, if more bed sediment is available for entrainment by overrunning turbidity currents. The downstream variation in net deposition \( (D-E) \) between subsequent numerical runs, totaling 48 h, is presented in Fig. 7B. The value of \( p = 0.03 \) was selected to depict a limiting case for which the right combination of upslope migration and vertical aggradation barely preserves the whole sequence in stratigraphy. Note that the downstream flanks of the waves migrate slightly upcurrent due to localized erosion rather than being preserved.

Levee formation is generally explained by a process of flow stripping (Piper and Normark, 1983). The development of sediment waves along the levees is a crucial part of the evolution of the channel-levee complexes (Migeon et al., 2000). Asymmetrical sediment waves form on the levees that are not too high to prevent the lowermost part of the channelized turbidity currents from overtopping. The coarser-grained stripped flows can, under the right conditions, generate trains of net-depositional upslope-migrating cyclic steps bounded by internal hydraulic jumps, as illustrated in Figs. 6A and 7A. As the asymmetrical sediment waves gradually build up in time, the associated levee becomes high enough to confine the lowermost
part of the channelized current. From this point on, only finer-grained turbidity currents, which are likely to have low spill-over energy (Migeon et al., 2000), can overtop the levee. Finer-grained turbidity currents spreading over asymmetric sediment waves can give rise to “inverse” asymmetrical or symmetrical sediment waves that in time build the levee at a particular location predominantly by aggradation. On the other hand, the coarser material concentrated in the lower part of turbidity currents can be confined within the channel, allowing for new fields of asymmetrical sediment waves to possibly form at a location farther downstream.

CONCLUSIONS

Upstream-migrating fields of cyclic steps are ubiquitous features in the deep ocean. Their formation, pattern of migration, and architecture are controlled primarily by the ratio of effective fall velocity to initial flow velocity, drop in bed Shields number across an internal hydraulic jump, inflow densimetric Froude number (inflow depth), mean grain size of sediment, availability of bed sediment for erosion, bed slope, presence and position of a slope break, inflow concentration of suspended sediment, porosity of bed sediment, and bed friction. The numerical model of submarine cyclic steps discussed here can be applied to any deep-sea system to predict the formation of turbiditic sediment waves or scour holes triggered by slope transitions. Recent improvements of the model allow linking of the evolution of turbiditic sediment waves to the channel-levee development, rendering the model particularly useful in the reconstruction of deep-sea systems and their flow hydraulics.

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Modeling of submarine cyclic steps


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