Enigmatic Bedforms in the Deep Sea

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ABSTRACT: Bedforms are ubiquitous features present in a full range of sedimentary environments. Recent work has identified the presence of large scale crescentic bedforms within submarine canyons and channel systems, related to gravity driven sediment laden turbidity currents that periodically flow though these systems. The formation and controls of these bedforms are not fully understood and their interpretation of the geological rock record is hampered by a lack of process-deposit knowledge for these systems and the bedform features they produce. This paper describes these enigmatic crescentic bedforms in the context of bedforms elsewhere, highlighting a range of novel and newly acquired datasets from Bute Inlet, Canada and Monterrey Canyon, USA. The paper discusses the interactions between the possible controls on their formation and how this is captured in the depositional record.

1 INTRODUCTION

Submarine channels act as conduits for turbidity currents, which have been identified to be the most volumetrically important processes for the delivery of sediment and organic carbon to the deep sea (Bouma 2000; Peakall et al., 2007; Paull et al., 2010; Hage et al., 2018). Turbidity currents are of great importance not only to our general understanding of global sediment transport processes, but also because of the environmental hazards they pose to subsea infrastructure such as communication cables or pipelines (Piper et al., 1999, Carter et al., 2014) and tsunamis related to submarine slope failures (Prior et al., 1982).

Bathymetric mapping of submarine canyon-channel-fan systems has recently revealed that these zones can be dominated by upslope migrating crescentic bedforms (Symons et al., 2016; Hage, et al., 2018) and recent system-scale wide process studies in submarine systems have demonstrated links between seafloor morphology, upward migration of crescentic bedforms, sediment distribution and the evolving flow (Hughes Clarke, 2016).

Combinations of numerical and physical experiments over a number of years have explored the formation of cyclic steps in turbidity current settings, which have been shown to typically generate deposits characterised by back-stepping beds (e.g. Spinewine et al., 2009, Postma and Cartigny, 2014, Covault et al., 2017). In contrast, many outcrops that have been interpreted as cyclic step deposits do not show these regular back-stepping beds, and can be frequently characterized by asymmetric scours filled with massive sands (e.g. Duller et al., 2008, Dietrich et al., 2016). Modern analogues for these massive sands have been reported in sediment cores collected from crescentic bedforms in Monterey canyon (Paull et al., 2011); and similar bedforms have been associated with cyclic steps on the Squamish Delta, B.C., Canada (Hughes Clarke, 2016).

Very recent work has also identified that flows over these bedform features can be initially driven by a fast moving, dense basal layer (Paull et al., 2018). However, fundamental questions remain regarding the sediment concentration of the flows, and whether the basal layer persists, or if flows transition to a state in which turbulence alone supports sediment and what and how this dense basal layer interacts with the bed morphology.

There is thus fundamental gap in understanding bedform dynamic in submarine canyon-channel-fan systems that is related to a need to obtain and integrate measurements from full scale supercritical turbidity currents, their associated bedforms and samples of their resultant deposits. Such integration, which has until very recently been out of reach, would allow the resolution of these discrepancies between model predictions of bedform dynamics and outcrop observations of bedform deposits from these settings.

Here we present the first combination of detailed (sub-minute resolution) 3D flow monitoring at multiple sites along a canyon-channel system, high-frequency seabed mapping, and sediment core data from two active turbidity current systems. The aims are to: 1) understand how crescentic bedforms are formed beneath supercritical flows; 2) use these observations to reconcile process mechanics and flow-form interactions and the elucidate discrepancies between existing experimental depositional models and outcrop observations; and 3) provide diagnostic criteria to confidently identify crescentic bedforms and thus supercritical flows in the geological rock record.

2 STUDY SITES AND DATASETS

Results will be presented from Monterey Canyon, USA and both Bute inlet and Squamish Inlet, Canada.

Bute and Squamish inlets are located on the western coastline of Canada. The fjords both have proximal detltas and have channels on the base of the fjords that extend, in the case of Bute, for over a length of 40 km. As such they represent modern examples of a submarine channel developing under the modification of turbidity currents (Prior & Bornhold, 1988; Conway, 2012).

Monterey canyon is located on the Pacific California mid coast extending from Moss Landing to over 2000 m.

2.1 *Morphodynamics measurements*

Modern bathymetric mapping and sampling techniques are increasingly being applied to submarine channel studies. Bathymetry was collected from a range of vessels across the study sites at different temporal resolutions, revealing unprecedented details of these types of bedform fields (Figure 1). This included daily surveys in Squamish and Bute Inlets to monthly repeat mapping using AUV in Monetary, targeted to map before and after distinct recorded events across a 12 month period. The data were analysed to understand the evolution of the bedform fields to compare bedform wavelength evolution with slope patterns formed by a range of supercritical flows.

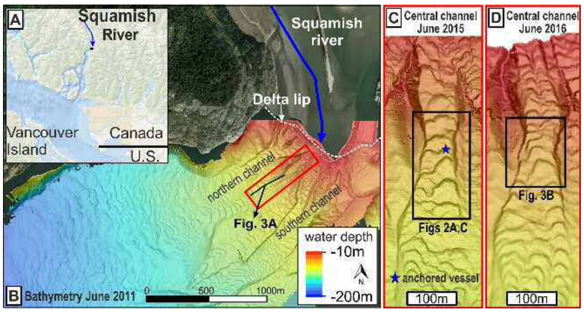

Figure 1. *A. Squamish river location. B. Downstream of the delta lie three submarine channels covered by crescentic bedforms. C. Location of flow dynamics observations, June 2015. D. Location of coring expedition, June 2016 (from Hage at al. 2018).*

2.2 Turbidity current monitoring

In both Bute and Monterrey a suite of fixed moorings, were deployed (e.g. Figure 2). Each had a range of equipment installed, including Acoustic Doppler Current Profilers (ADCP). Moorings were placed within the submarine channel axis positioned from the proximal areas to the distal lobe of the system in the case of Bute and to over 1850 m in Monterey.

Flow and acoustic backscatter data were recorded for at least five months in each system. These captured the passage and evolution of episodic supercritical turbidity currents as they progressed through the channel systems.

In Bute, more than 20 turbidity currents were observed during this 5 month period. Most of the flows dissipated in the proximal part of the channel system with 11 events observed at 10 km downstream from the proximal delta. The supercritical turbidity currents drive an observed upstream migration of the knickpoints and reorganise some of the larger bedforms during each event.

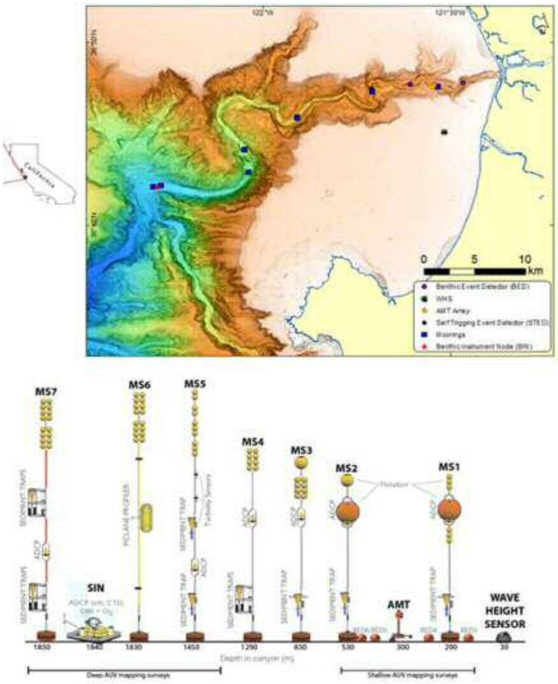

Figure 2. Map and schematic of the moorings in Monterey canyon experiment.

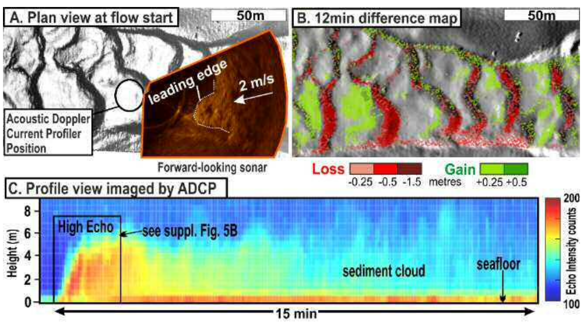

***Figure 3.** Observations of a turbidity current linked to crescentic bedforms A: Snapshot showing a plan view of the flow traveling over the bedforms; B: Seafloor change 12 min after the flow displayed in A & C; C: Time series view the turbidity current from Acoustic Doppler Current Profiler (location in A) (from Hage et al., 2019).*

In Monterey a total of 15 flows were observed (Figure 4) by the instruments during the entire 18 month study period. Three of these flows ran out through the full array of instruments to past 1850 m water depth. The largest of these, on January 15th 2016, transported heavy objects several kilometres down the upper canyon. Our acoustic inversions demonstrate that, even for the largest of the flows, the suspended sediment concentration remains relatively dilute (<1%). But that the flows are driven by near-bed high-concentration basal layers.

2.3 Acoustic Inversion and Noise

As mentioned above, Acoustic Doppler Current Profilers have previously been deployed in submarine channels to measure density current flow structure and suspended sediment concentration at a single location. Within the Monterey Coordinated Canyon Experiment, the most detailed study of a submarine channel undertaken thus far, which demonstrates how flows evolve as they pass through an array of instruments (Figure 4). Paull et al. (2018) have demonstrated that the flows are initially driven by a fast moving, dense basal layer. However, fundamental questions remain regarding the sediment concentration of the flows, and whether the basal layer persists, or if flows transition to a state in which turbulence alone supports sediment.

Our acoustic inversions demonstrate that, even for the largest of the flows measured in the canyon, the suspended sediment concentration remains relatively dilute (<1%). However, periods of elevated acoustic noise were observed in the ADCP data commencing with flow arrival at the moorings. This phenomenon was observed for all flows and was only occasionally absent in the some of the distal observations of the flows. We infer that the noise is generated by particle collisions from a high concentration of sediment (> 9%) around the top of a dense basal layer that is mostly less than 1 m thick. We conclude that dense basal layers are present for the majority of the duration of the flows and that dilute suspensions run out for only a relatively short distance beyond the terminal location of the front of the dense layer.

We relate the magnitude of the particle collision noise to the velocity of the top of the basal layer and demonstrate that there is low shear between the dense layer and overlying dilute suspension in the body of the flows. This helps to explain the large density contrast (two to three orders magnitude) between the thin dense layer and the dilute suspension just a few meters above.

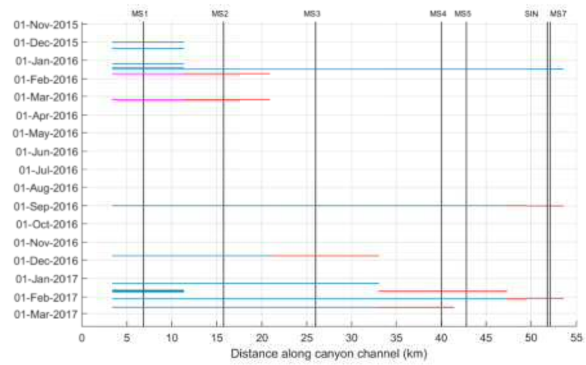

Figure 4: *Timing and runout of monitored flows in Monterey Canyon. Vertical lines indicate the locations of the moorings and along the canyon channel. Horizontal lines represent the observed sediment density flow events. Blue lines indicate the presence of particle collision noise and red lines indicate where flow velocities and backscatter were observed without particle collision noise. Magenta lines indicate the likely occurrence of events at the MS1 location in the period after the instruments detached from the mooring anchor (Simmons et al., in prep).*

For the largest flow on January 15th, the longest observed duration of the particle collision 51 noise is ~ 1 hour 50 minutes at ~780 m water depth. In contrast, the shortest duration of ~ 52 30 minutes was observed at the distal end of the array (Figure 5). The basal layer stretched as it progressed down the canyon and was still flowing over a distance of greater than 26 km by the time the flow front reached the most distal mooring. The particle collision noise for this flow ceased nearly simultaneously at all moorings between ~780 m to ~1850 m water depth, indicating that the dense basal layer slowed so a similar speed at the same time over a vast distance along the canyon floor.

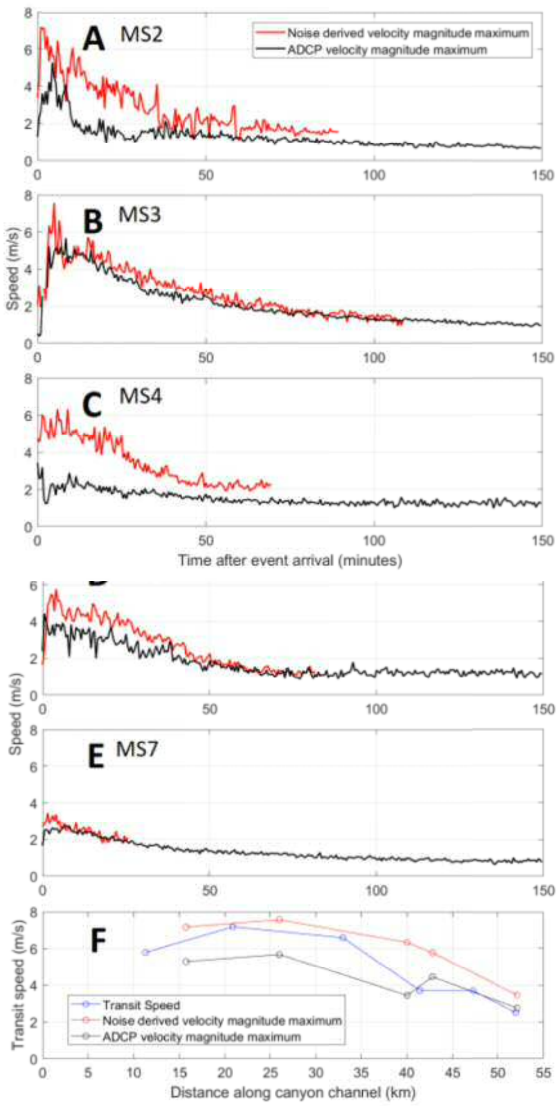

Figure 5: *Velocity maximum from ADCP data and basal flow velocity derived from the particle collision noise for the five moorings that recorded data during the Jan 15 event, (F) flow speed derived from particle collision noise compared with the maximum ADCP velocity and transit speeds between the moorings (from Simmons et al., in prep).*

2.4 Deposits

Hage et al. analyse four months of near-daily bathymetrical surveys to study the stratigraphic evolution resulting from upstream migration of crescentic bedforms. The uppermost part of the stratigraphy (Fig. 3a) contains up to 3 m thick successions of individual beds that dip upstream. Individual back-stepping beds are 0.1 m to 0.5 m thick and result from the most recent turbidity current depositing sediment on the stoss-side of the bedform thus causing them to migrate upstream. They show that occasionally, large flows cause significant upstream migration of the bedforms, eroding the seafloor deeper and producing thicker, back-stepping beds. The lower portion of these thicker upstream migrating beds is preserved typically as 1 m to 2 m thick lens-shaped scour fills, as seen in the lower part of the final stratigraphy (Figure 6).

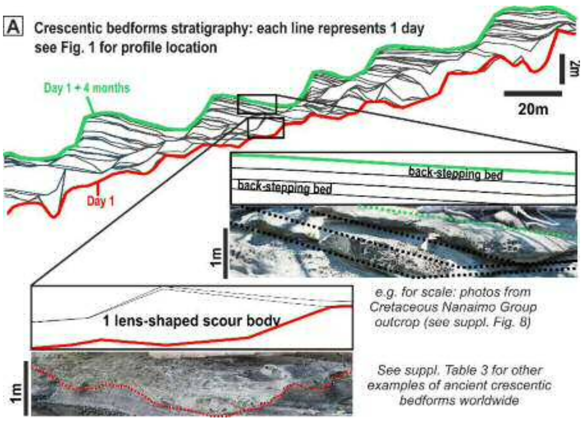

Figure 6. *Along-strike stratigraphy computed from 106 bathymetrical surveys and comparison of the features with ancient crescentic bedforms deposits (from Hage et al., 2019).*

Additional to the computed stratigraphy a set of cores to sample the facies characteristics were also acquired. The sediment cores all contain multiple units of massive sands, which are ungraded to poorly graded. Contacts between beds are sharp and erosive. Individual beds are therefore inferred to result from individual turbidity currents (Figure 7).

Envisaged deposit architectures can range between two end-members: 1) regular back-stepping beds that correspond to a full bedform preservation; 2) scours filled with massive sands that correspond to low bedform preservation (Figure 7). The preservation potential of these bedforms depends on both the magnitude of the formative turbidity currents and the net aggradation rates and the dynamics of any dense basal layers in the largest flows.

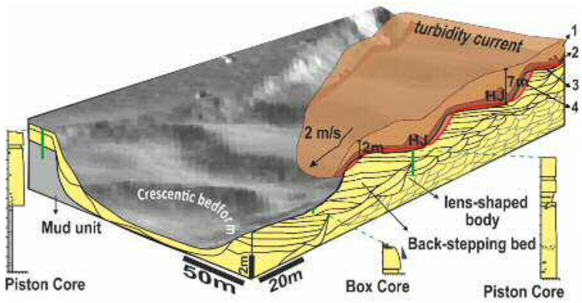

Figure 7. *Summary schematic of crescentic bedforms formed by supercritical turbidity currents and their depositional architecture. 1: Low density upper part of the flow, 2: High density lower part of the flow with hydraulic jump formed on changing gradient over bedforms, 3: Deposition & 4: Erosion by active event. Red line corresponds to the resulting bathymetry after a single flow. Black lines are observations from Fig. 3A. Grey lines are predictions (from Hage et al., 2019).*

3 SUMMARY

Crescentic bedforms in submarine canyon-channel-fan systems are enigmatic features. A suite of novel data has been collected from three systems where crescentic bedforms and ubiquitous. The results reveal a complex relationship between turbidity current flow characteristics, sediment transport dynamics, and the possible presence of a dense basal layer. The results are allowing insight into these processes and what these processes can produce in terns of signatures in the rock record.

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