The influence and interactions of delta slopes and knickpoints on bedforms within submarine channel systems

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ABSTRACT: Submarine channels play a vital role in delivering vast quantities of sediment to the deep sea, forming some of the largest sediment deposits on Earth. Knickpoints have been identified as an important morphological feature of many submarine channel systems. Knickpoint features have superimposed crescentic bedforms, which are formed by the action of supercritical turbidity currents. The interactions between bedform dynamics, supercritical flows, and channel morphology remain poorly understood on these environments, and a better understanding of the dynamics would enable improved linkages to be made between the morphological evolution of submarine channels and the deposits they generate. Here we present a suite of wavelet analyses of repeat bathymetric survey data from Bute inlet, British Columbia, Canada, take over a 10 year period, from 2008 to 2018. The results show how dominant crescentic-shaped bedform wavelengths are affected by spatial and temporal changes in delta slope and how knickpoint migration generate down-channel bedforms.

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 has revealed that proximal sections of submarine channels can be dominated by upslope migrating crescentic bedforms (Symons et al., 2016; Hage, et al., 2018). Another morphological feature of the channels are knickpoints, which are described as an abrupt change in river gradient (Whipple and Tucker, 1999). Knickpoints are known to play a major mode in governing channel adjustment in response to either regional or local perturbations (Gilbert, 1896; Holland, 1974; Hayakawa and Matsukura, 2003; Baynes, 2018). Recent system-scale wide process studies in submarine systems have demonstrated links between seafloor morphology, upward migration of crescentic bedforms, sediment distribution, flow and the depositional record (Hughes Clarke, 2016; Hage et al., 2018).

Here we describe new perspectives on bedform development in submarine channels gained by studying a sequence of bathymetric data acquired over a 10 year period in Bute inlet, British Columbia, Canada. Our study explores the relationships between delta slope, channel knickpoint dynamics and the response of crescentic bedforms in terms of their heights, wavelengths and migration. The results have implications for our understanding of bedforms in these channel systems and furthering our understanding of their development, sediment dispersal and deposition and thus longer-term submarine channel evolution.

2 STUDY SITE

Bute inlet, British Columbia, is located on the western coastline of Canada. The fjord has a length of over 40 km and represents a modern example of a submarine channel developing under the modification of turbidity currents (Prior & Bornhold, 1988; Conway, 2012) (Fig. 1). The channel extends to a depth below the water surface of 700 m at the distal part of the fjord, where it terminates in a lobe feature. The two main rivers, the Homathko and Southgate, discharge into Bute Inlet at the head of the fjord. Trites (1995) estimated the total mean annual freshwater flow into the fjord to be approximately 410 $m^3 s^{-1}$ of which 280 $m^3 s^{-1}$ is from the Homathko River. Discharge to Bute Inlet is highly seasonal, peaking in July because of snow and ice melt from the interior watershed. The lowest input occurs in the winter months as the precipitation is stored as snow in the higher elevation of the watershed. The mean annual discharge can also vary year to year (Fig. 2).

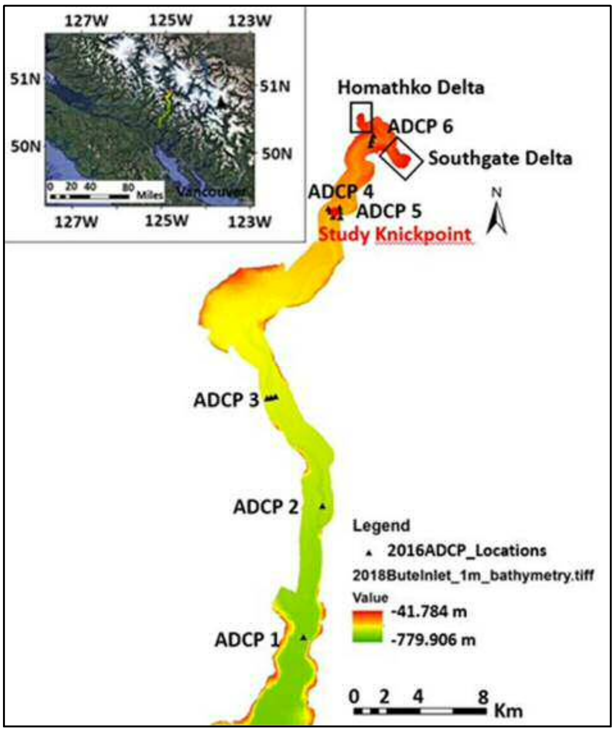


Figure 1. Bute Inlet location in British Columbia

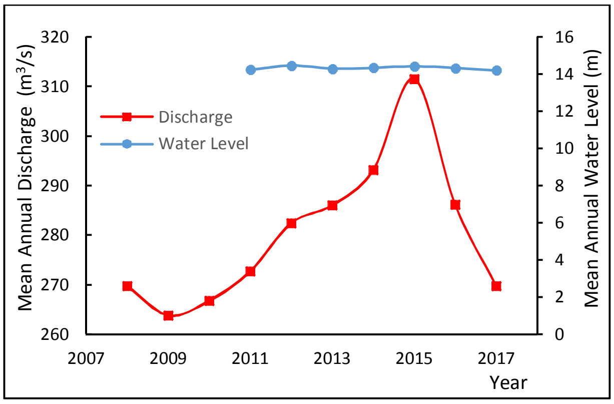


Figure 2. Mean annual discharge and water level of the Homathko River

3 METHOLOGY AND MATERIAL

3.1 Bathymetry measurement

Modern bathymetric mapping and sampling techniques are increasingly being applied to submarine channel studies (Sumner et al., 2013; Xu et al., 2014; Dorrell et al., 2016; Clare et al., 2016; Hughes Clarke, 2016;

Azpiroz-Zabala et al., 2017; Paull, 2018; Hage et al., 2018). Here we analyse repeat multibeam bathymetry data from Bute Inlet acquired over a 10 year period from 2008 to 2018. We additionally analyse high resolution multibeam echo-sounder bathymetry data from Homathko and Southgate deltas taken in 2016 and 2018, to compare bedform wavelength evolution with slope patterns formed by supercritical flows and flows with characteristic differences between 2016 and 2018 (Fig. 3.2).

3.2 Turbidity currents

Six Acoustic Doppler Current Profilers (ADCP) were deployed on six moorings within the submarine channel axis positioned from the proximal delta to the distal lobe of the system (Fig. 1). Flow at one mooring and acoustic backscatter data were recorded for five months beginning in June 2016. These captured the passage and evolution of episodic supercritical turbidity currents as they progressed through the channel system (Fig. 1). 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 the study knickpoint, 10 km downstream from the proximal delta. The supercritical turbidity currents drive an observed upstream migration of the knickpoint during each event. Thus, this comprehensive system-scale data set enables us to explore the relationship between turbidity current frequency, flow duration, flow velocity and long-term changes in delta morphology and knickpoint retreat.

3.3 Wavelet analysis

The wavelet analysis was conducted using the Bedforms-ATM (Bedforms analysis toolkit for multiscale modelling) software (Gutierrez et al., 2018). By adapting the one dimensional continuous wavelet analysis package developed by Torrence et al (1998), the software performs wavelet analysis of along-channel transects containing multiple bedforms. The resulting wavelet spectrum demonstrates information about the dominant constituent wavelengths along the channel as a function of distance along the channel. Values are screened out that fall outside a cone of influence that discriminates reliable power spectrum results from spurious measurements (Gutierrez et al., 2018).

4 RESULTS

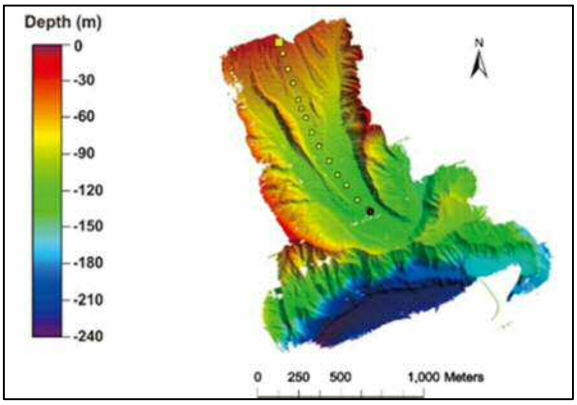
4.1 Bedform scales in the Homathko and Southgate deltas

The Homathko River contributes around 80% of the discharge that flows into Bute Inlet. Digital elevation model analysis reveals that the delta has experienced periods of both degradation and aggradation during the range of hydrological conditions during the study period. The subaqueous channel geomorphology is shown in Fig. 3a. Dozens of small flow pathways can be observed at the delta lip until the water depth reaches ~ 75 m. The small flow pathways then merge into three main channels in the mid-section, and then into a single channel at the distal end of the delta slope at ~ 115 m depth. Trains of crescentic bedforms occupy the delta slope area and periodically migrate upslope.

Wavelet analysis allows an unravelling of the complex relationship between bedforms of different scales and the underlying channel morphology. Fig. 3b shows the delta slope decreasing from around 7° at the delta lip to 4° at the distal end. Small scale crescentic bedform wavelengths are formed both in the delta lip and close to the distal end of the slope. In the mid-section of the delta slope, the wavelet power spectrum shows dominant bedform wavelength of around 32 m to 50 m. The wavelength increases as the delta slope becomes lower. However, small scale wavelengths and larger wavelengths are both present at the distal part of the delta, which indicates perhaps enhanced variability in the turbidity currents, which flow through this zone.

The wavelet power spectrum of the bedform profiles along the central channel at Southgate (Fig. 4b) shows a greater variation in wavelength from one end of the section to the other, corresponding to a larger decrease in channel gradient, from 9°

to 3.5°. The Southgate delta morphology has a deeper delta lip and a flatter delta distal zone compared with the Homathko delta. A main channel with large-scale cresentic bedforms is located at the north side of the delta and few smaller channels exist in the central section. In the south section of the delta a narrower shallow channel exists. All channels merge into one wider conduit at a depth of ~130 m. The delta slope declines from around 9° to 3.5° from proximal to distal. As shown in the wavelet analysis results, crescentic bedform wavelengths gradually become longer as the water depth increases and delta slope declines.



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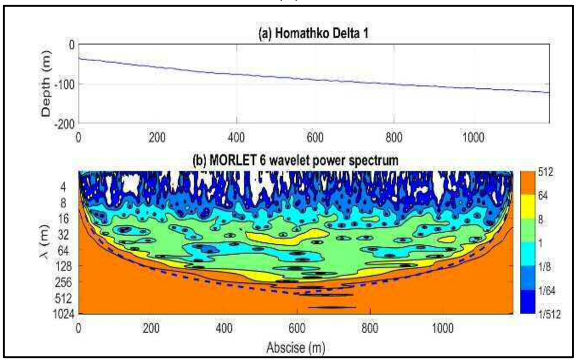
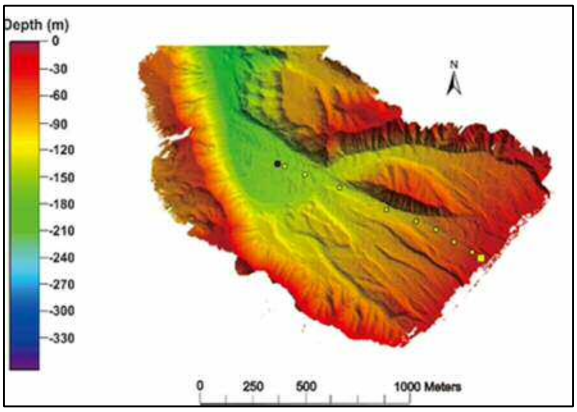


(b)

Figure 3: (a) Geomorphology of Homathko delta shown by bathymetry data; (b) Wavelet power spectrum of one profile along the central channel in the delta



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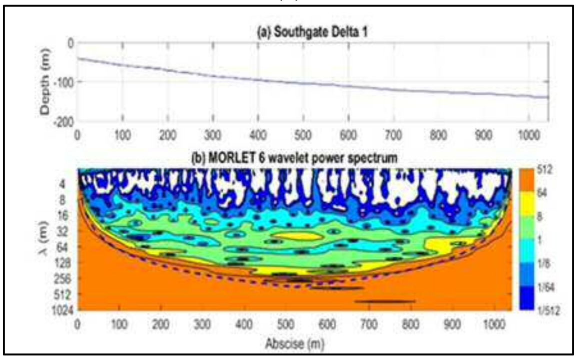
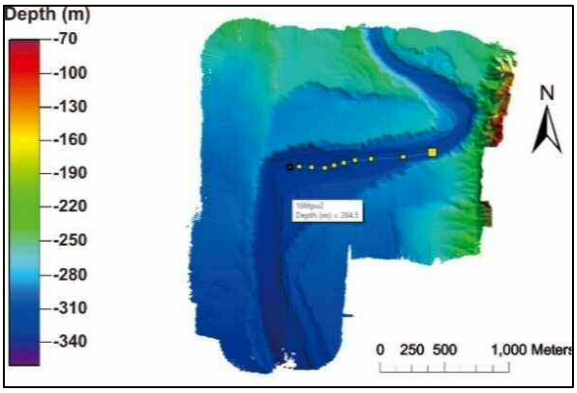


(b)

Figure 4: (a) Geomorphology of Southgate delta shown by bathymetry data; (b) Wavelet power specturm analysis of one profile along the central channel in the delta

4.2 The impact of knickpoint retreat on submarine channel bedforms

The repeat seafloor mapping reveals significantly different knickpoint geometries on June 2016 (Fig. 5a&b) and May 2018 (Fig. 6a&b). Superimpsoed bedforms patterns of different scales are in evidence before and after knickpoint migration within the wavelet analysis results (Fig. 5). Bedform wavelength in June 2016 increased alongside upstream knickpoint migration. Extended bedforms occurred within a region of ~380 m downstream of the knickpoint. Further downstream the bedforms return to a lower wavelength that are similar to the bedforms upstream of the knickpoint. The bedform scale change indicates the influence of the knickpoint morphology on bedform dynamics due to the influence of the knickpoint on passing turbidity currents.



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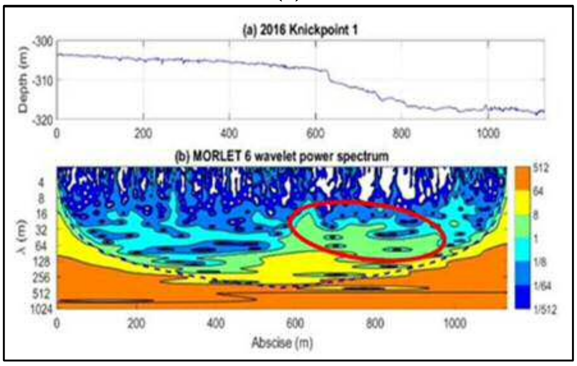
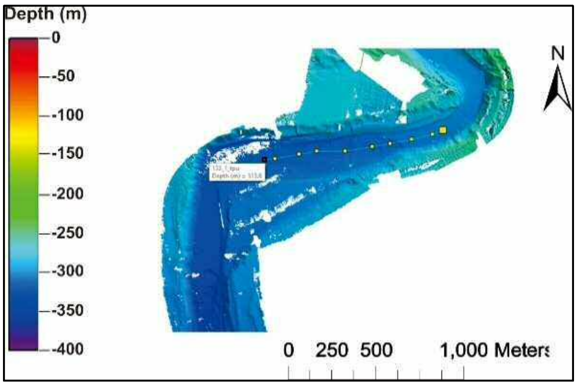


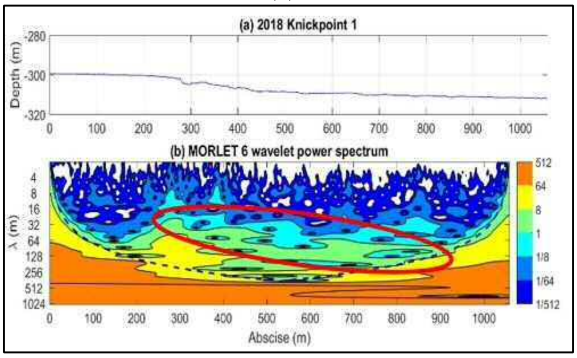
(b)

Figure. 5 (a) Geomorphology of the study knickpoint in June 2016; and (b) the wavelet power spectrum of an along-channel transect across the knickpoint from 2016

The wavelet power spectrum from the May 2018 survey (Fig. 6a and b) shows similar bedform scale patterns to June 2016. However, a few extremely long-wavelength bedforms, varying from ~ 64 to ~ 150 m, are present downstream of the knickpoint, perhaps suggesting that the recent set of currents have significantly different hydrological conditions compared to those in 2016.
According to hydrological monitoring data acquired in the Homathko River (Environment Canada), the discharge to the delta was lower 2017 than 2016 (Fig. 2). Therefore the hydraulic parameters of turbidity currents could be different between the two years, which may be a factor in the generation of the longer wavelength bedforms in 2017. However, more work is needed to relate bedform dimensions to the formative currents.



(a)



(b)

Figure. 6 (a) Geomorphology of a study knickpoint in May 2018; (b) the wavelet power spectrum of an along-channel transect across the knickpoint from 2018

5 CONCLUSIONS

The results of a wavelet power spectrum analysis demonstrate how delta slope and knickpoint morphologies can influence the scales and geometries of channel bedforms. Upstream knickpoint migration redistributes sediments and the pattern of bedform wavelengths in the channel. Long-wavelength bedforms occurred downstream of the knickpoint following a lower input discharge entering the delta system in 2017, possibly resulting in changes to the turbidity current characteristics and dynamics and subsequent changes in bedform morphology. This study is enabling us to explore the role of delta slope on controlling the size and shape of crescentic bedform geometries and also allows us to explore how knickpoint migration sculpts and influences overall bedform distributions and the links to longer-term submarine channel dynamics.

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