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# A threshold in submarine channel curvature explains erosion rate and type

Zaki Zulkifli [a,b,c,*], Michael A. Clare [a], Maarten Heijnen [a], D . Gwyn Lintern [d], Cooper Stacey [d], Peter J. Talling [e], Matthieu J.B. Cartigny [e], Timothy A. Minshull [b], Hector Marin Moreno [b], Jeffrey Peakall [f], Stephen Darby [g]

[a] *Ocean BioGeoscience, National Oceanography Centre, Southampton, European Way, UK*
[b] *School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton, UK*
[c] *Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Terengganu, Malaysia*
[d] *Geological Survey of Canada, Institute of Ocean Science, Canada*
[e] *Departments of Earth Sciences and Geography, Durham, UK*
[f] *Department of Earth and Environment, University of Leeds, UK*
[g] *School of Geography and Environmental Sciences, University of Southampton, Southampton, UK*

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## ABSTRACT

Submarine channels are conduits for sediment-laden flows called turbidity currents, which play a globally significant role in the offshore transport of sediment and organic carbon and pose a hazard to critical seafloor infrastructure. Time-lapse repeat surveys of active submarine channels have recently shown that upstream-migrating knickpoints can dominate channel evolution. This finding contrasts with many studies of ancient outcrops and subsurface geophysical data that inferred channel bends migrate laterally, as occurs in meandering rivers. Here, we aim to test these two contrasting views by analysing two high-resolution repeat seafloor surveys acquired 13 years apart across the entirety of an active submarine channel in Knight Inlet, British Columbia. We find that two main mechanisms control channel evolution, with the normalised channel radius of curvature (specifically, $R^*$ - channel radius of curvature normalised to channel width) explaining which of these mechanisms dominate. Pronounced outer bend migration only occurs at tight bends ($R^*<1.5$). In contrast, at broader bends and straighter sections ($R^*>1.5$), erosion is focused within the channel axis, where upstream-migrating knickpoints dominate. High centrifugal accelerations at tight bends promote super-elevation of flows on the outer channel flank, thus, enhancing outer bend erosion. At $R^*>1.5$, flow is focused within the channel axis, promoting knickpoints that migrate upstream at an order of magnitude faster than the rate of outer bend erosion at tight bends. Despite the dominance of knickpoints in eroding the channel axis, their stratigraphic preservation is very low. In contrast, the lateral migration of channel bends results in much higher preservation via lateral accretion of deposits on the inner bend. We conclude that multiple mechanisms can control evolution at different channel reaches and that the role of knickpoints has been underestimated from past studies that focused on deposits due to their low preservation potential.

## 1. Introduction

Submarine channels are the primary conduit for the transfer of sediment from shallow to deep water and occur on most continental slopes worldwide (Mulder, 2011). Globally-important quantities of sediment and organic carbon are transported through these channels by density flows called turbidity currents (Azpiroz-Zabala et al., 2017; Rabouille et al., 2019; Talling et al., 2024). Submarine channel deposits form some of the most significant sediment accumulations on our planet, creating substantial hydrocarbon reserves, stratigraphic archives of climate change, and carbon burial (Babonneau et al., 2010; Clift and Gaedicke, 2002; Covault et al., 2014; Sylvester and Covault, 2016). Other than being a significant contributor to deep-sea sediment transport (e.g., Paull et al., 2018), turbidity currents also pose a threat to seafloor infrastructure, including hydrocarbon pipelines and the global network of seafloor cables that provide critical energy and communications (Carter et al., 2014; Sequeiros et al., 2019). Therefore, it is vital to understand which processes control sediment transport and storage in

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* Corresponding author at: Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Terengganu, Malaysia
*E-mail address:* zakizulkifli@umt.edu.my (Z. Zulkifli).

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submarine channels and over which timescales, as this governs the hazard posed to seafloor structures, the efficiency of organic carbon burial, and the nature of sediment transfer to the deep sea.

Despite many studies over the past decades, there remains disagreement about which mechanism is the dominant control on submarine channel evolution. First, upstream-migrating crescentic bedforms have been proposed to play a dominant role in channel evolution on steep slopes such as the continental slope where high Froude numbers are favoured. They act as a building block of such depositional systems, from the proximal channel axis, levee-overbanks, down to the channel-lobe transition zone (Covault et al., 2014, 2017; Hamilton et al., 2015; Vendettuoli et al., 2019). Such bedforms have been linked to fast-moving turbidity currents that undergo a switch (hydraulic jump) from Froude super- to sub-critical conditions as they pass over the bedform (Spinewine et al., 2009; Hughes Clarke, 2016; Covault et al., 2017; Hage et al., 2018), and are common, particularly within the proximal reaches of many submarine channels worldwide, (e.g., Symons et al., 2016; Covault et al., 2017; Hage et al., 2018). Depending on the aggradation rate of the system, the resultant deposits are preserved either as low-angle, backstepping beds (high aggradation) or lenticular bodies (low aggradation), typically comprising massive sands (Hage et al., 2019).

Second, the upstream migration of steep steps in channel gradient, known as knickpoints (that can be tens of metres high), has recently been suggested to play an even more critical role in channel evolution (e. g. Guiastrennec-Faugas et al., 2020; 2021; Heijnen et al., 2020). Submarine knickpoints may form as a result of erosion by a turbidity current undergoing a large hydraulic jump, due to retrogressive collapse of a steep downstream slope, or due to sediment build-up at tight bends, or some combination of these processes (Heijnen et al., 2020; Guiastrennec-Faugas et al., 2021). The rate of knickpoint migration (100–450 m/year) in submarine channels may exceed that of equivalent features in rivers by 2–6 orders of magnitude, depending on substrate strength and discharge (Heijnen et al., 2020). Knickpoint migration results in localised but pronounced (tens of metres) down-cutting into previously emplaced channel axis deposits and forms tabular channel-wide deposits, which are also focused within the channel axis (Mitchell, 2006; Heijnen et al., 2020). Despite these recent studies demonstrating the important role of knickpoints in shaping modern active systems, the identification of knickpoints in ancient systems remains sparse, with few studies providing clear evidence of their deposits (e.g. Heiniö and Davies, 2007; Stright et al., 2017; Tek et al., 2021; Allen et al., 2022).

Finally, the lateral migration of channel bends has also been inferred to play a key role in submarine channel evolution (e.g. Peakall et al., 2000, 2007; Babonneau et al., 2010; Kolla et al., 2012; Jobe et al., 2016; Palm et al., 2021). Channel bends have been observed from seafloor and subsurface seismic surveys, particularly on large deep-sea fans and in many of the lower reaches of deep-sea submarine channels (e.g. Peakall et al., 2007; Babonneau et al., 2010). While submarine channel bends may share many morphological similarities with rivers, the nature of flow within submarine channels and the morphology of expansion of bends can vary from that observed in rivers (e.g. Peakall et al., 2000; Peakall and Sumner, 2015; Covault et al., 2021). However, the overall pattern of erosion in submarine channels is focused on the outer bend, while deposition occurs on (or just downstream of) the inner bend, forming laterally accreted packages of sediment and/or oblique accretion deposits (Peakall and Sumner, 2015). Abundant evidence of lateral accretion packages that indicate channel bend migration has been found in many ancient submarine channel systems worldwide (e.g. Abreu et al., 2003; Dykstra and Kneller, 2009; Babonneau et al., 2010; Jobe et al., 2016).

There are thus many different potential mechanisms that may control submarine channel evolution; however, the limited number of examples of directly monitored modern active submarine channel systems and their geomorphic evolution, means that the factor (or factors) that are most dominant remain unclear (e.g. Talling et al., 2015). Past studies have focused mainly on depositional archives (subsurface geophysical imaging, sediment coring, and ancient outcrops, (e.g. Zeng et al., 1991; Babonneau et al., 2010; Covault et al., 2016), supplemented by scaled-down analogue laboratory experiments (e.g. Keevil et al., 2006), and numerical modelling (e.g. Giorgio Serchi et al., 2011; Sylvester et al., 2011; Tian et al., 2023). Therefore, most observational studies analyse the resultant deposits, which are highly incomplete due to punctuated erosion caused by successive flows (e.g. Silva et al., 2019; Vendettuoli et al., 2019). Laboratory and numerical models (e.g. Keevil et al., 2006; Sylvester and Covault, 2016) provide useful insights into channel evolution, but whilst flow fields have been examined at field-scale (Parsons et al., 2010; Wei et al., 2013; Sumner et al., 2014; Azpiroz-Zabala et al., 2024) there remain few studies that have examined flow processes and channel evolution in natural channels, particularly ones that cover the entirety of a channel system (e.g. Hughes Clarke, 2016; Paull et al., 2018; Gales et al., 2019). As a result, there is a compelling need for a field-scale study that focuses on flow processes in channel evolution.

Recent advances in repeat seafloor mapping now enable field-scale monitoring of submarine channel evolution at high temporal (minutes to years) resolution and provide the opportunity to test deposit-based models and hypotheses (e.g. Hughes Clarke, 2016; Paull et al., 2018; Heijnen et al., 2020). While such monitoring campaigns face many challenges (e.g. accessibility, high cost, and infrequency of events; Talling et al., 2015), a growing number of active submarine channels have now been repeatedly mapped over the past decade to better understand the nature of the processes that shape them (e.g. Conway et al., 2012; Hughes Clarke, 2016; Paull et al., 2018; Silva et al., 2019; Vendettuoli et al., 2019; Heijnen et al., 2020). Most of these channel systems that have been time-lapse surveyed are in relatively shallow (<600 m) water on steep slopes and remain only partially surveyed (i.e. not from source to sink). However, insights gained from repeat bathymetric surveys allow us to address key questions about how and why channels evolve.

## 2. Aims

In this paper, we analyse repeat seafloor surveys acquired 13 years apart that cover the entirety of a modern, active submarine channel system (from river source to termination at a deep-sea lobe) in Knight Inlet, British Columbia, Canada. Such extensive surveys are rare; we know of only one published study that has repeatedly surveyed from source to deep-sea sink (Heijnen et al., 2020). We aim to answer the following questions: First, which processes dominate the evolution of the submarine channel in Knight Inlet? Previous studies have identified crescentic bedforms, channel bends and knickpoints in Knight Inlet and other submarine channels in similar fjord settings (Conway et al., 2012; Gales et al., 2019). New repeat seafloor mapping data allow us to quantify the amount of net erosion and net deposition attributed to these different processes and understand how they shape the channel. We see that different reaches of the channel are affected to a different extent by these various processes. This motivates our second question. Why does the influence of these processes (bedform migration, outer bend erosion, and knickpoint migration) vary spatially along the channel? We investigate whether channel morphology and its influence on flow behaviour explain the nature and rate of erosion and migration. The curvature of river and tidal channel systems has been shown to play a vital role in controlling meander bend growth rate (e.g., Hickin and Nanson, 1975; Finotello et al., 2018; Sylvester et al., 2019), so we ask whether a similar control exists in submarine channels. Finally, what is the likely preservation of stratigraphic evidence for the different mechanisms that influence channel evolution? We compare the depositional signature of the different processes and discuss if their variable preservation potential may bias the interpretation of processes that operated and dominated in ancient submarine channel systems.

## 3. Data and methods

We analyse two bathymetric surveys acquired in 2005 and 2018 in Knight Inlet, British Columbia, Canada. The surveys cover the full extent of a 41 km-long submarine channel system, which extends from two prodeltas fed by the Klinaklini (responsible for 80% of the sediment supply; Bornhold et al., 1994) and Franklin Rivers to a terminal lobe at approximately 450 m water depth (Fig. 1). Sediment supply from these two rivers is seasonally variable, mainly supplied during the spring and summer freshet due to snowmelt. Previous measurements using seafloor current meters have shown that many (at least 25–30) turbidity currents occur each year within the submarine channel and are most likely during windows of heightened river discharge (Bornhold et al., 1994); as observed in other submarine channels in the region (e.g. Howe Sound – Hughes Clarke, 2016). River discharges in the winter are typically below 100 $m^3/s$ but can reach peaks of 1200 $m^3/s$ in the spring and summer (Bornhold et al., 1994). Sediments in the submarine channel are typically fine to coarse sands, with silt and clay deposits dominating the areas outside the channel (Ren et al., 1996).

Bathymetric data were obtained using a Kongsberg Maritime EM710 (70–100 kHz) multibeam echosounder deployed from the RV Vector operated by the Canadian Coastguard Service. Data were gridded into 5 m x 5 m bins for the 2005 survey and 2 m x 2 m for the 2018 survey. The vertical resolution of the data is <0.5% of the water depth (Conway et al., 2012; Hughes Clarke et al., 2014). Hence in the deepest water (~450 m) surveyed here, this vertical resolution is 2.25 m.

The bathymetric data were analysed using ESRI ArcGIS software. Greyscale slope maps were generated to visualise channel morphology, and a raster calculator was used to generate differences in elevation between the two surveys. As part of this process, the 2018 2 × 2 m bin-size survey was re-sampled to match the coarser 5 × 5 m gridding of the 2005 survey. In the bathymetric difference maps, red colours indicate areas of net erosion (negative values), while blue colours indicate areas of net deposition (positive values). Confidence in the calculated elevation differences is reduced at the edges of the survey area (i.e. well outside the channel limits) and where elevation differences were equal to or below the vertical resolution of the bathymetric data. Seabed elevation changes and eroded volumes were calculated using the raster calculator tools in ArcGIS software. Channel width was calculated by measuring the horizontal distance orthogonal to the channel axis between breaks in slope on the channel flanks. We measure the channel width at the apex of each bend. This measurement was completed manually, and each flank was selected manually as the point where flows could overflow outside the channel. The mean channel width is 236 m. Sinuosity, defined as the ratio between the length along the channel and the straight-line distance between the endpoints, was calculated using the RiverMetric package in QGIS software. Sinuosity was calculated every 10 m down the channel over a length scale of 1000 m. The mean channel sinuosity is 1.76. The location for the measurement of the radius of curvature was decided purely by visual fitting at the arc of the channel bend, which was measured in ArcGIS for each of the channel bends (Fig. 2). The measurement of the radius of curvature is achieved through a circle that most nearly fits the curve of a given channel bend (Weihaupt, 1989). In order to compare observations at Knight Inlet with other systems, we present a normalised radius of curvature $R^*$, where for each bend, we divide the radius of curvature, $R$, by the local channel apex width ($B$), following a widely-adopted approach for terrestrial rivers first applied by Hickin and Nanson (1975). Radius of curvature is the inverse of the channel curvature ($1/R$). Fig. 1 shows how the measurements are made in this study.

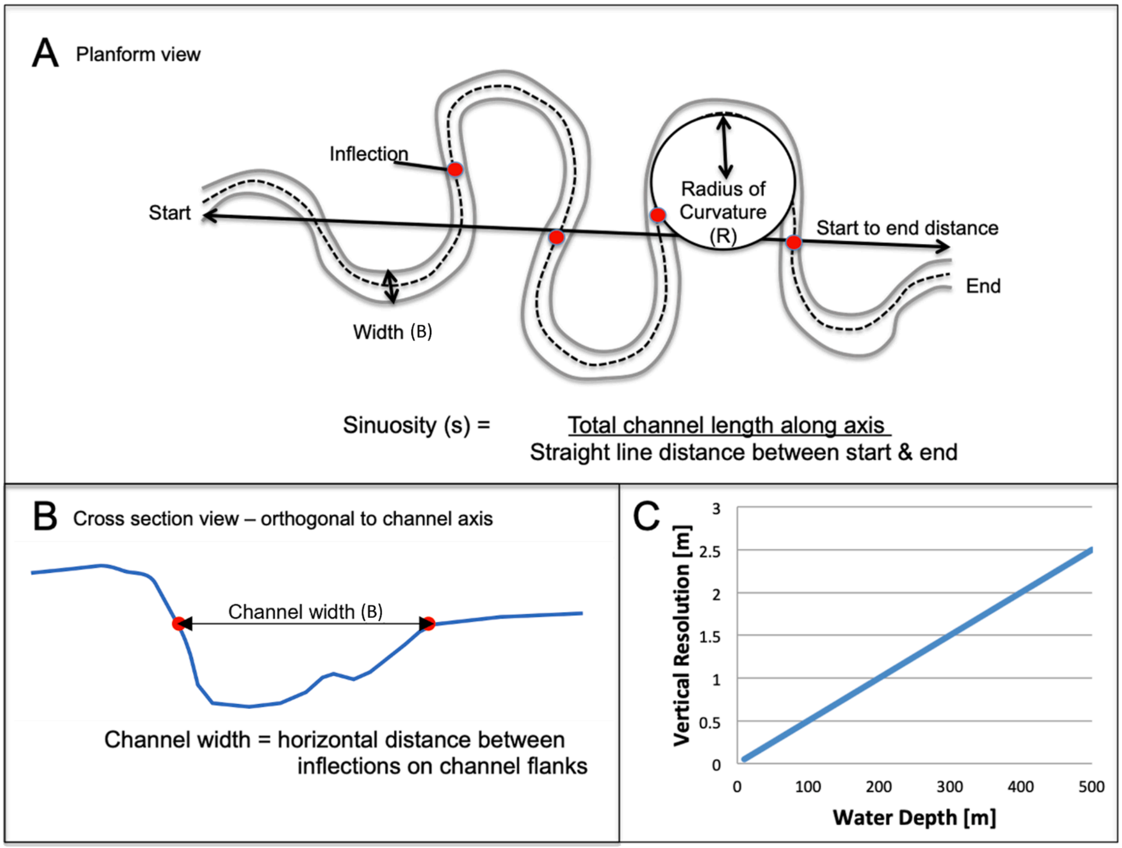

**Fig. 1.** Illustration of measurements made in this study. A) Planform view of the channel to illustrate sinuosity, radius of curvature and channel width. B) Cross-section view to illustrate the measurement of channel width, which was taken orthogonal to the channel axis. C) Plot showing how the vertical resolution of the multibeam bathymetric data changes as a function of water depth.

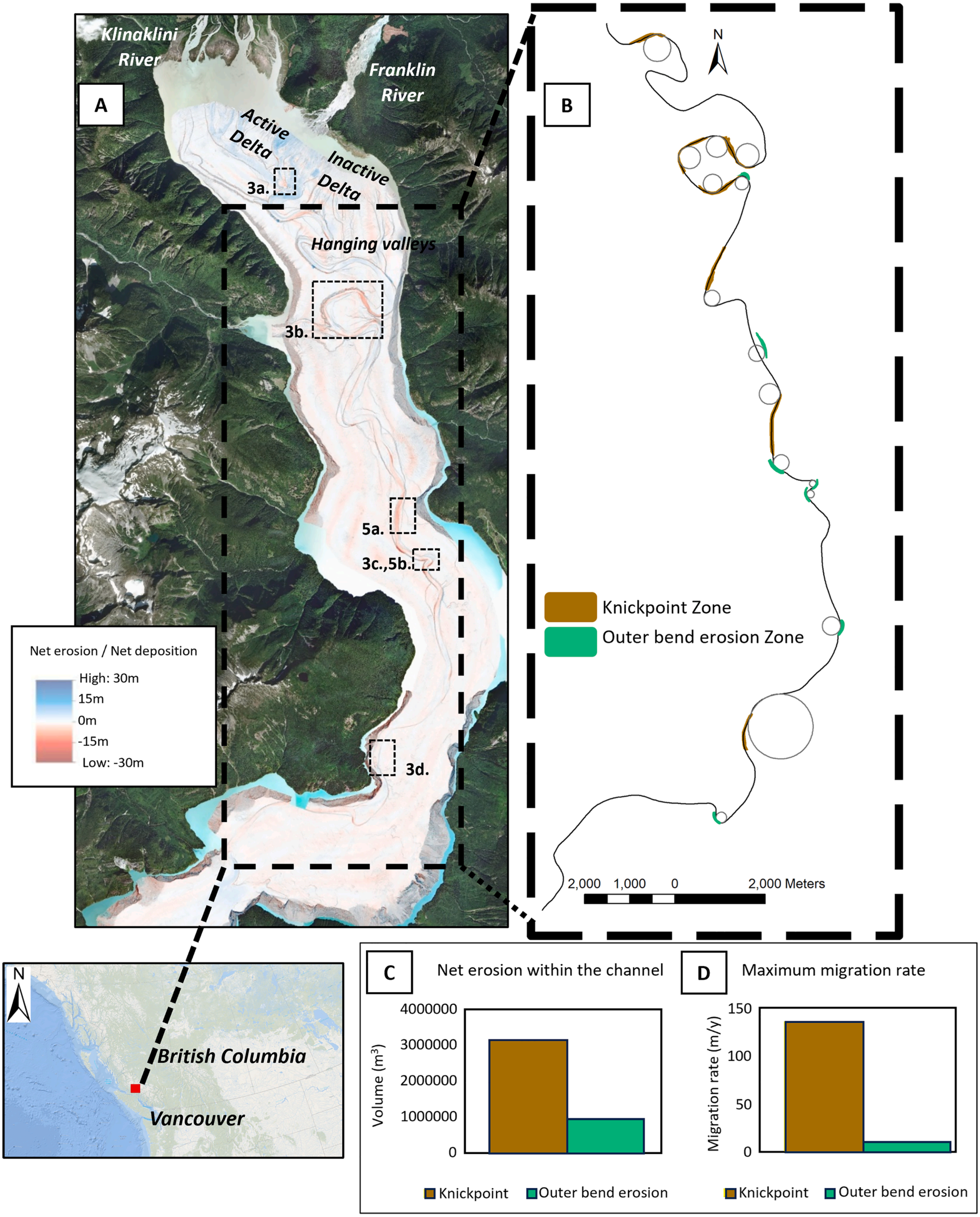

**Fig. 2.** (A) An overview of the seabed elevation change between 2005 and 2018 for the study area, illustrating locations that are detailed in Fig. 3. (B) Radius of curvature for the channel bends along the submarine channel, annotated with the locations where erosion related to knickpoints or outer bend migration was identified. (C) Total net eroded volumes over 13 years, differentiating that relating to knickpoints and outer bend erosion. (D) Maximum migration rate measured for knickpoints (distance upstream) and at channel bends (distance orthogonal to the channel axis) over 13 years.

## 4. Results

Differences in elevation above the vertical resolution of the bathymetric data are observed at several locations along the full length of the channel, from the prodelta that forms the start of the submarine channel to the lobe at the channel's deep-water terminus (Fig. 2). Three different types of seafloor change are observed over the thirteen-year interval: i) crescentic bedform migration and associated local channel incision; ii) upstream-migration of knickpoints; and iii) lateral migration of channel bends. We now highlight where these seafloor changes occur within the submarine channel at Knight Inlet.

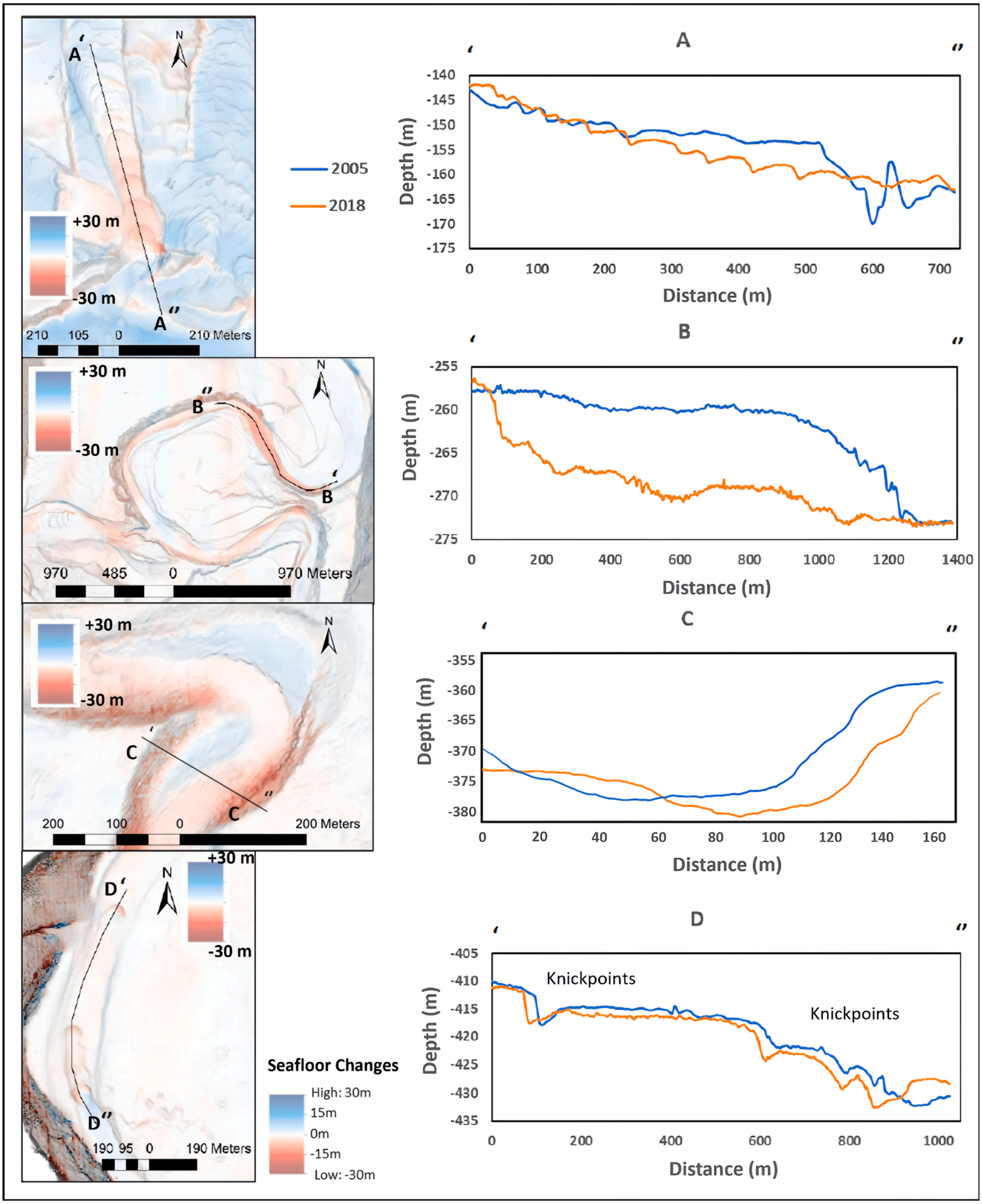

**Fig. 3.** Examples of changes in seabed elevation in planform maps and cross sections. (A) Example of migrating bedforms in the proximal prodelta channel. (B) Up-channel migration of a major knickpoint. (C) An example of outer bend erosion. (D) Changes due to migration of a minor knickpoint. See Fig. 2a for locations.

### 4.1. Processes responsible for seafloor change

#### 4.1.1. Crescentic bedforms on the prodelta slope

The steep (~5°) submarine prodelta front at the channel head is dominated by crescentic bedforms, which have typical wavelengths of 10 m and amplitudes of 5 m (Fig. 3a). Bedforms are observed across the entire prodelta front, but discernible elevation changes (i.e. above the vertical resolution of the data, which is <0.5 m here) are only seen down-stream of the Klinaklini and Franklin Rivers (herein termed the 'active delta'; a locus for sediment accumulation of up to 9 m vertically). This area is not solely net aggradational, as a new channel has been locally incised (up to 5 m depth), cutting a new pathway that is covered with crescentic bedforms (Fig. 3a). As bathymetric resolution reduces in greater water depths, it is possible that such features may occur farther down the channel, but they cannot be imaged reliably.

#### 4.1.2. Upstream-migration of knickpoints

Farther downslope from the prodelta, where a single channel is established on an average slope of 1.4°, the upstream-migration of up to 5–10 m-high knickpoints, with steep headwalls (~40°) dominates several reaches of the channel (Fig. 3b and d). Knickpoints occur at multiple points along the channel (Fig. 2), including distinct 10 m-high isolated knickpoints at 270 m, 280 m and 300 m water depth, a series of three 5 m-high knickpoints that migrate upstream up to 1 km around a large channel bend between 260 m and 300 m water depth (Fig. 3b), and one small (5 m-high) knickpoint at 425 m water depth (Fig. 3d). The elevation change for this latter smallest knickpoint is close to the vertical resolution of the multibeam data at this depth. Hence, we cannot be fully confident in its migration. However, the changes for the other larger and shallower water knickpoints far exceed the vertical resolution at their equivalent water depths, and those larger knickpoints clearly migrate upstream. Erosion created by the migration of knickpoints results in up to 10 m of elevation change, which is almost exclusively focused within the axis of the channel. Occasionally there is some minor erosion focused towards the outer bend of the channel where a series of three knickpoints occur in the large channel bend (Fig. 3b).

#### 4.1.3. Lateral migration of outer bends

We observe localised erosion focused on the outer flank of some, but not all, bends throughout the channel system. The most prominent erosion of this type is observed at the tightest ($R^*$<1.54) channel bend, which is located about 23 km down the channel at 375 m water depth (Fig. 3c). The outer flank of the channel shifted 30 m laterally, resulting in up to 20 m vertical erosion. Up to 6 m sediment thickness accumulated on the inner bend, forming a point bar that accreted 10 m laterally (Fig. 3c).

### 4.2. Migration rates and eroded volumes

It is not possible to determine an upstream migration rate for the crescentic bedforms that dominate the relatively steep prodelta slope, as the same bedform crest cannot be reliably identified in multiple surveys. Those crescentic bedforms likely migrated many times during the 13-year period between surveys (e.g. Vendettuoli et al., 2019). We thus observe a time-averaged pattern of net sediment accumulation on the prodelta, with local incision by minor channels. Knickpoints show the fastest channel migration rates of all the observed bedform features, with a maximum measured upstream movement of 1625 m (Fig. 4), which equates to an average-migration rate of 136 m/year. In contrast, the lateral channel migration observed at outer bends is much lower, with a maximum observed lateral shift in the channel flank of only 67 m, which equates to an average migration rate of 5.6 m/year. The minimum total volume of sediment eroded by knickpoint migration is $3.18 \times 10^6$ $m^3$, compared to the $9.34 \times 10^5$ $m^3$ attributed to outer bend erosion. Thus, it seems that knickpoints dominate the erosion (accounting for ~77% of the total) observed in this channel system, but their influence is not equal along the full length of the channel and is highly spatially variable.

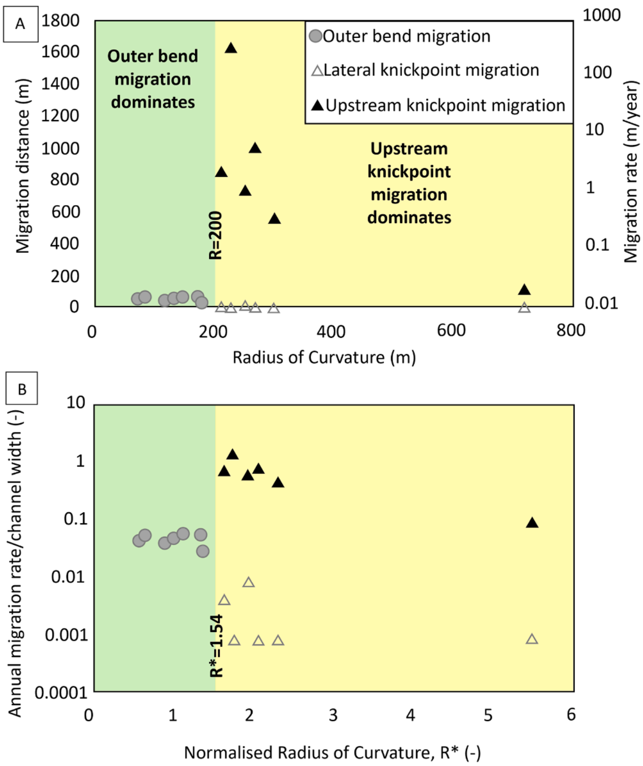

**Fig. 4.** (A) A threshold in the radius of curvature ($R = 200$ m) is observed, above which rapid upstream migration of knickpoints occurs with only limited outer bend erosion, while outward bend erosion dominates below the threshold. (B) Migration rates and radii of curvature are normalised to channel width, showing that a $R^* \sim 1.5$ threshold for the normalised radius of curvature appears to control the rate and nature of erosion – dictating whether knickpoints or outer bend erosion will dominate.

### 4.3. Channel curvature explains whether knickpoints or outer bend erosion dominate

Alternations between reaches characterised by knickpoint migration or outer bend erosion occur along the channel length and show no clear relationship with distance from the active delta (Fig. 2). Downslope of the prodelta, overall channel gradient remains constant (1.4°) and is not a major control on channel evolution. Instead, we find that outer bend erosion only dominates at the tightest bends in the system (Fig. 4a), where the normalised radius of curvature of the channel is below a threshold value of $R^* = 1.54$ (Fig. 4b). In contrast, when $R^* > 1.54$ (i.e. the straightest sections of the channel), erosion is dominated by knickpoints that migrate at a faster rate, upstream and around the bend, rather than orthogonal to the bend (Fig. 4b). Where $R^*$ slightly exceeds 1.54 (i.e. around the broad looped bend; Fig. 3c), knickpoints tend to swing towards the outer edges of the channel, which leads to some, albeit minor, erosion on the outer bend. However, where $R^* >> 1.54$ (i.e. the straightest channel sections), erosion is exclusively focused within the channel axis (Fig. 5d). The normalised radius of curvature of the channel appears to correspond to locations where erosion is either dominated by outer bend ($R^*$<1.54) or knickpoint migration ($R^*$>1.54).

## 5. Discussion

We first discuss the processes that dominate erosion in the submarine channel in Knight Inlet and how and why channel-normalised radius of curvature may correlate with the type and rate of erosion observed. We

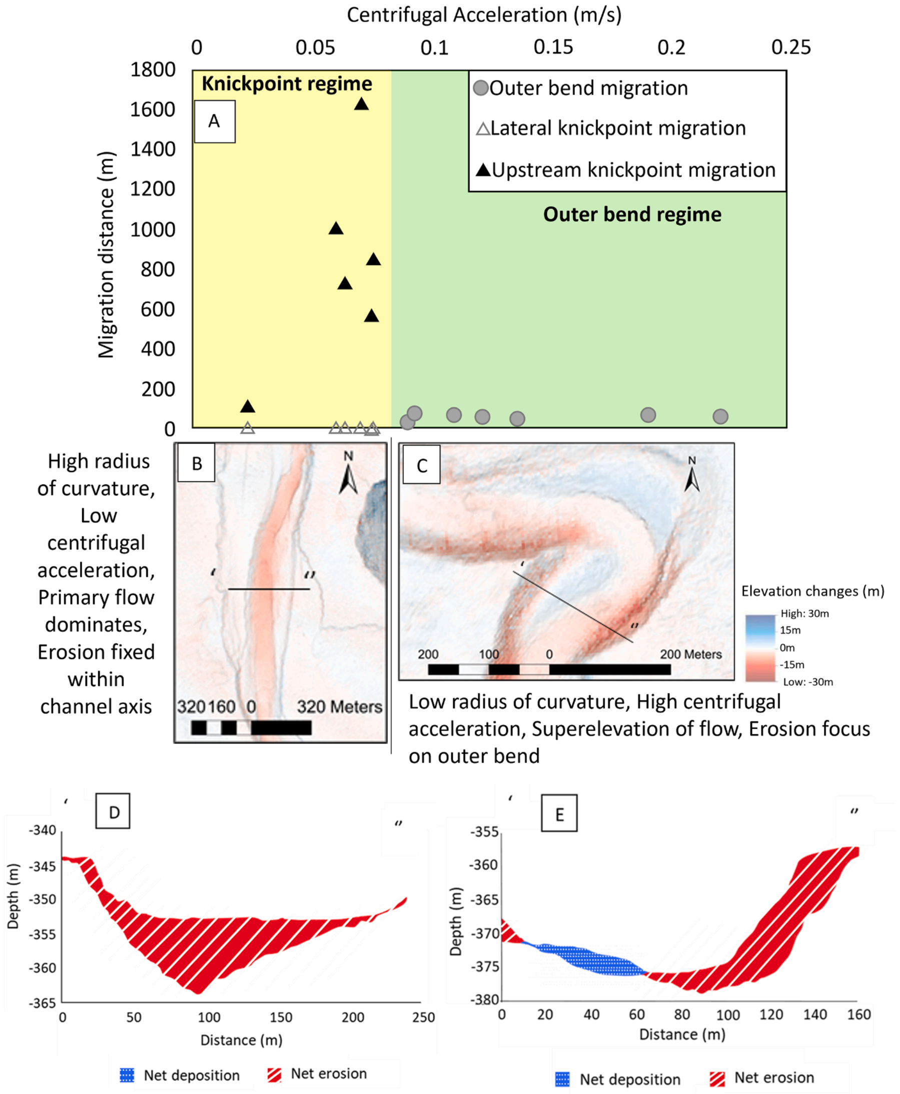

**Fig. 5.** Centrifugal accelerations derived at erosion locations based on flows with an assumed primary velocity of 4 m s$^{-1}$ compared with the migration distance (A). Erosion is focused within the channel axis at low centrifugal accelerations (B,D), prompting knickpoint incision. In contrast, secondary circulation plays a more important role at high centrifugal accelerations, deflecting the primary downstream velocity towards the outer bank and consequently focusing erosion on the outer bend (C,E).

compare our findings to observations from fluvial and tidal channels and discuss their implications for reconstructing past flow behaviour from ancient submarine channel deposits.

### 5.1. Knickpoints dominate submarine channel erosion

We show that net erosion in the submarine channel at Knight Inlet is dominated (77%) by upstream-migration of knickpoints rather than outer bend erosion (23%). This study thus contributes to a growing recognition that knickpoints play a key role in channel evolution, as in the nearby Bute Inlet (Heijnen et al., 2020) and Capbreton Canyon in the Bay of Biscay (Guiastrennec-Faugas et al., 2020; 2021). Even in the case of the most prominent channel bend in Knight Inlet, a series of three knickpoints was observed to migrate almost 1 km upstream around the bend rather than undergoing lateral migration across the bend and enlarging the channel. This focus on erosion within the channel axis likely explains the long-term preservation of this channel bend, which was first observed in low-resolution seafloor surveys acquired in the late 1980s and has not experienced any cut-off in that time (Bornhold et al., 1994; Ren et al., 1996; Conway et al., 2012).

### 5.2. Why does channel bend radius of curvature dictate the mode of erosion?

Outer bend erosion does play a significant role, however, in some bends. We found that some sections of the channel (where bends are tightest; $R^*<1.54$) are dominated by outer bend erosion, and the traces of knickpoints cannot be identified. Therefore, we now explore why the nature and rate of erosion differ so markedly depending on normalised radius of curvature. Frequent turbidity currents are known to occur within Knight Inlet (Bornhold et al., 1994), and given the similarities in their source-type, triggering, channel morphology and seafloor substrate, it is reasonable to assume that their nature is similar to flows (of up to 4 m s$^{-1}$) that have been measured in detail in other nearby fjord-head submarine channel systems (Bornhold et al., 1994; Hughes Clarke, 2016; Hage et al., 2019; Chen et al., 2021). Flows that travel around a bend experience centrifugal acceleration, which is defined by:

$$F = U^2/R$$

where $F$ is centrifugal acceleration, $U$ is the velocity of the flow, and $R$ is the radius of curvature. Thus, centrifugal acceleration will be higher at tighter (i.e., lower radius) channel bends, and if we assume turbidity currents in this system have a nominal velocity of 4 m $s^{-1}$, a threshold for outer bend erosion occurs when the centrifugal component of flow, $F >$ 0.08 m $s^{-1}$. Higher centrifugal accelerations around channel bends create super-elevation of the flow on the outer bend of the channel, setting up a helical secondary (i.e. cross-channel) flow that directs the primary downstream flow towards the outer bank resulting in enhanced erosion (Dorrell et al., 2013; Sylvester et al., 2019). In straighter (i.e. higher radius of curvature) sections of the channel, the influence of centrifugal acceleration is diminished, and flows will show much less super-elevation, limiting the potential for outer bend erosion. Enhanced flow super-elevation, and enhanced secondary flow, are thus inferred to explain why outer bend erosion only occurs at the tightest (lowest radius of curvature) channel bends (Fig. 5e). In fluvial systems, the primary forcing of this curvature-induced outer bank erosion has been debated, driven either by deposition at the inner bend (bar push), or by erosion at the outer bank (bank pull) which then drives inner bend deposition (Eke et al., 2014). However, in submarine channels, outer bend erosion (bank pull) has been argued for, creating space for the inner bend deposits (Peakall and Sumner, 2015; Palm et al., 2021). Consequently, it is probable that this curvature-induced outer bend erosion is driving the evolution of these channel bends (Fig. 5e).

Recent studies in modern systems have suggested that knickpoint erosion is associated with high Froude number flows, with erosion enhanced on the steep downstream step as the over-riding flows undergo a hydraulic jump (Guiastrennec-Faugas et al., 2020; 2021; Heijnen et al., 2020; Chen et al., 2021). In moderate amplitude bends, approaching the transition point of $R^* = 1.54$, a combined effect of helical flow fields resulting from centrifugal acceleration and Froude-supercritical flow may occur wherein upstream-migration of knickpoints dominates. However, the focus of erosion may swing towards the outer bend (as seen in Bute Inlet and the Capbreton Canyon) (Heijnen et al., 2020; Guiastrennec-Faugas et al., 2020; 2021) due to the influence of centrifugal acceleration on the flow field (Fig. 6). Therefore, we address previous contradictions concerning which process dominates channel evolution, showing that different processes can dominate different reaches of the same submarine channel (i.e. no one process fully dominates). This variation likely results from the localised variations in the curvature of the channel and hence its relative influence on the primary and secondary flow of turbidity currents. Channel curvature plays an important role in not only controlling the rate of erosion but also the nature of erosion. Once a knickpoint is formed, its migration dominantly up the channel, rather than orthogonal to it, may itself lead to a straighter section of the channel forming between knickpoints. Hence, we infer that it is possible that a positive feedback loop exists between the channel morphology and the mechanism of erosion.

Herein we have focused on the centrifugal force and the role of curvature, as reflected in the observations, but it is instructive to examine the role of the centrifugal force in more detail. The centrifugal force that deflects the primary downstream flow laterally is a function of both radius of curvature and velocity, and therefore changes in velocity would also be expected to alter the transition point. Given this, it is perhaps surprising that the transition between curvature and processes — outer bend erosion and knickpoints — is as clear and sharp as it is. For individual bends, the answer to this apparent paradox likely lies in the observations that most geomorphic work is associated with bankfull flows (Wolman and Miller, 1960) and that sinuous submarine channels act to filter the maximum size and thus the velocity of the flows that traverse them through flow stripping at bends (Amos et al., 2010). As a consequence, the variation in velocity, at a given bend, for channel forming flows may not be a key parameter and thus radius of curvature is the controlling characteristic. Nonetheless, flows will progressively decelerate downstream, albeit the rate at which this deceleration occurs in Knight Inlet is unknown. Such deceleration will lead to a progressive decrease in the angle of secondary current deflection towards the outer bank relative to the primary (downstream) flow, so it might be expected to alter the value of $R^*$ at which this transition occurs. The present study has too few bends to examine whether such a spatial variation in distance occurs, and as noted, it also lacks the velocity data needed to test this idea. Longitudinal variations in velocity will similarly affect knickpoint processes, but again the influence of such changes for now remains unknown.

### *5.3. Channel curvature influences migration rate and its direction relative to the channel axis*

Channel curvature is also an important control of meander bend migration rate in terrestrial rivers and shallow water channel systems. Normalising radius of curvature, $R$, to channel width, $B$, to give $R^*$, enables migration rates to be compared between rivers and tidal channels. Previous studies have found that bend migration is highest at a normalised radius of curvature of $R^* \approx 3$, wherein rates of migration drop off rapidly on either side of that value (Hickin and Nanson, 1975; Finotello et al., 2018). Note that curvature can also be analysed continuously around a bend, and in that case it has been argued that there is no decrease in migration rates in the very tightest bends, when allowing for the observed spatial lag between maximum curvature and maximum migration (Sylvester et al., 2019; 2021). Herein, however, we use a single measure of normalised radius of curvature, $R^*$, for a bend following the approach of Hickin and Nanson (1975) in order to enable comparison across a range of channel environments.

In comparison, annual migration rates, when normalised for channel width (0.021–0.043 m/year/channel width), for channel bends below our observed normalised radius of curvature threshold (equivalent to $R^* < 1.54$) are broadly comparable to mean values reported for rivers and tidal channels worldwide (~0.03 m/year/width; Finotello et al., 2018). Whilst using the continuous curvature approach, Covault et al. (2020, 2021) also showed a strong relationship between migration rate and channel curvature for submarine channels. In the present study, for values of $R^* > 1.54$, however, there is a significant departure. Specifically, the observed rates of outer bend erosion at Knight Inlet are at least an order of magnitude lower than those in rivers and tidal channels at $R^* > 1.54$. At Knight Inlet, we see a dominance of upstream-focused knickpoint migration, which themselves migrate at least an order of magnitude faster than those in rivers. Physical experiments of submarine channel systems have suggested that the migration rate will reduce as the radius of curvature decreases (Dorrell et al., 2018), in keeping with the eventual near cessation of movement of high sinuosity bends in many systems (Peakall et al., 2000). However, these experiments did not feature an erodible bed, so knickpoints could not form, and these experiments may lack key features of Knight Inlet (Dorrell et al., 2018). What is common, however, is that these observations indicate that the relationships that exist for fluvial and tidal channels do not extend to submarine channels shaped by turbidity currents. Specifically, in the present case we show a marked break in migration rates as a function of normalised radius of curvature, and show that knickpoint dominated bends have much lower migration rates than equivalent fluvial and tidal bends. This study of Knight Inlet thus adds to a growing body of research that concludes that turbidity currents have a distinct behaviour from rivers, due to the reduced density contrast between the flow and the ambient surrounding medium, their propensity to super-elevate and run up slopes due to momentum, their often-variable density stratification, and the nature of secondary circulation as they travel around channel bends (e.g. Peakall and Sumner, 2015; Jobe et al., 2016; Shumaker et al., 2018). We also recognise that other factors that could not be tested in this study may play a contributory role, such as contrasts in density, cohesion or mechanical strength between the substrate outside the channel compared to that within the axis (Schumm, 1963). Future studies should aim to provide constraints to these physical properties.

As knickpoint incision develops, the vertical incision may start to entrench the axis of the channel, further inhibiting the development of bends and lateral migration of the channel, creating a positive feedback.

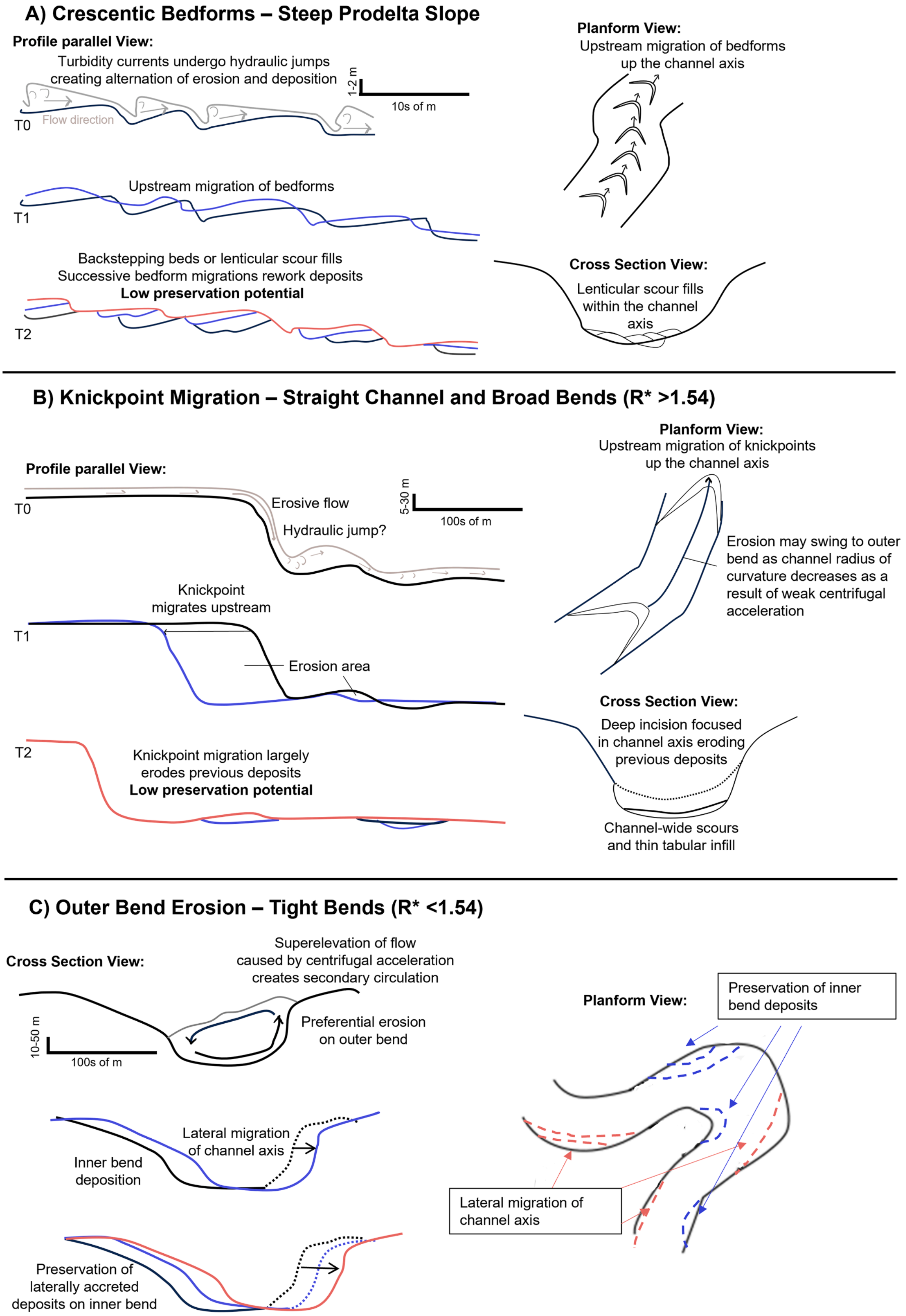

**Fig. 6.** Illustration of how different processes influence channel evolution. (A) Crescentic bedform processes that dominate the steep prodelta slope. (B) The process of knickpoint migration that dominates straight channels and broad bends. (C) The process of outer bend erosion that dominates at tight bends.

This raises the question of how tight bends initiate in such channel systems. However, the present dataset does not allow this question to be explicitly answered. We postulate that perhaps some other perturbation to the morphology is required, as could be created by channel wall collapse (resulting from lateral flank-steepening during knickpoint incision) that asymmetrically widens the channel locally, or due to collapse of material into the axis that creates a new topographic barrier that reroutes turbidity currents. More temporally closely spaced time-lapse surveys are required to document any such events, and enable processes to be examined in more detail.

We consider it broadly reasonable that other similarly active submarine channel systems may behave according to our model; however, we recognize that other factors may cause some deviation. The nature of transported sediment controls the substrate that accumulates, eroding differently based on whether it is granular or cohesive (e.g. Mastbergen and van den Berg, 2003; Winterwerp et al., 2012). Subsurface and tectonic features can steer flows and affect erosion or deposition. Shallow sub-cropping or outcropping bedrock, mobile subsurface salt or mud, fault scarps, and neotectonics can influence the course and steepness of submarine channels, potentially deviating from our model (Heinio and Davies, 2007; Mitchell, 2014; Micallef et al., 2014; Covault et al., 2021; Mitchell et al., 2021). Morphologic disturbances like flank collapses can alter the channel morphology and change erosion rates (Covault et al., 2024). Biological effects, which are not included in our model, can also modify erosion rates (e.g. Azpiroz-Zabala et al., 2024). Thermohaline-driven bottom currents influence the evolution of submarine channels, often creating asymmetry and unidirectional migration (e.g. Miramontes et al., 2020; Fuhrmann et al., 2020). We hope our model spurs testing and future surveys to quantify erosion rates globally, ideally with three-dimensional flow data to enhance understanding of flow dynamics.

### 5.4. *Why have knickpoints been under-reported from depositional records?*

Repeat seafloor surveys in Knight Inlet and other systems now show that knickpoints can dominate erosion in active, deep-sea submarine channels, and knickpoints are increasingly being recognised from new high-resolution seafloor surveys of submarine channels around the world (e.g. Ceramicola et al., 2014; Gales et al., 2019; Guiastrennec-Faugas et al., 2020, 2021; Heijnen et al., 2020; Chen et al., 2021). Despite this apparent importance of knickpoints, evidence of knickpoints remains sparse from studies of ancient systems, in contrast to abundant examples of outer bend erosion and development of meandering channels (e.g. Dykstra and Kneller, 2009; Babonneau et al., 2010; Sylvester et al., 2011; Maier et al., 2012; Jobe et al., 2016). While the migration rates associated with knickpoints are up to an order of magnitude higher than that for outer bend erosion in Knight Inlet, Bute Inlet and Capbreton Canyon, knickpoints remain focused within the channel/canyon axis. Successive reworking by crescentic bedform migration has been shown to result in very low stratigraphic preservation potential on prodeltas and proximal areas of the submarine channel. For example, <11% of the deposits that accumulated in the axis of submarine channels on the submerged Squamish Delta over one year remained in place, as they were subsequently reworked and redeposited further downstream (Vendettuoli et al., 2019); only lenticular sand bodies were preserved that represent the infill of scours at the base of bedforms with their uppermost parts stripped and reworked (Hage et al., 2019; Englert et al., 2020). As successive knickpoints can migrate upstream through the same section of the channel over time (Heijnen et al., 2020), they also likely rework or remove much of the evidence of the preceding knickpoint or any crescentic bedforms. Therefore, the diagnosis of knickpoints from ancient outcrop-based depositional records may be especially challenging, relying upon the identification of erosion surfaces, relatively thin, tabular channel fill packages, or rapid changes from lag deposits to fine-grained sediments on preserved terraces (Tek et al., 2021; Allen et al., 2022). In contrast, the lateral migration of the channel axis at tight bends means that depositional packages form on the inner bend of the channel, as well as erosion on the outer bend. These laterally-accreting inner bend deposits thus have a much higher preservation potential than either crescentic bedforms or knickpoints. Timelapse surveys performed by Guiastrennec-Faugas et al. (2021) and Heijnen et al. (2022) reveal that the presence of knickpoints within the depositional record may not be preserved beyond annual timescales. We, therefore, conclude that this contrast in preservation potential explains the apparent under-recognition of knickpoints compared to outer bend erosion from ancient depositional archives and that previous models based on such records may have similarly under-represented the role of knickpoints in the life cycle of submarine channels. However, improvements in the acquisition and processing of seismic data, coupled with a greater process-based understanding has meant that the diagnostic signature of knickpoints is starting to become better recognised (e.g. Sylvester and Covault, 2016; Hansen et al., 2017; Tek et al., 2021). This present study contributes to a growing body of literature that reveal the diagnostic criteria for knickpoint identification, including their morphology, scale and now the reaches of a channel that may be more prone to knickpoint migration. Future studies should aim to look for pronounced erosion surfaces, tabular, channel-confined fills, and rapid vertical grain-size transitions on terraces to investigate the significance of knickpoints.

## 6. Conclusions

Based on repeat seafloor surveys across the entirety of a submarine channel in Knight Inlet, British Columbia, we document changes in elevation between 2 surveys conducted 13 years apart. These time lapse surveys are used to investigate the controls on channel evolution. Upstream-migration of crescentic bedforms dominates the steep (5°) prodelta slope, while upstream-migration of knickpoints accounts for 77% of the observed erosion in the rest of the channel system, dwarfing that attributed to outer bend erosion. Different reaches of the channel are affected to different degrees by these contrasting processes. However, we show for the first time that channel curvature exerts a strong influence on which process will dominate and the overall rate of migration. Tight channel bends ($R < 200$ m; $R^* < 1.54$) are dominated by outer bend erosion, which we relate to enhanced centrifugal acceleration that drives super-elevation of turbidity currents and focuses erosion on the outer bend. In contrast, broader channel bends and straighter sections of the channel ($R > 200$ m; $R^*>1.54$) are locations where knickpoints cut deep (up to 20 m) into the channel axis, migrating much faster (up to 136 m/year upstream) compared to the rate of outer bend erosion (up to 6 m/year orthogonal to the channel axis). Despite the apparent dominance of knickpoints in sculpting the channel, we suggest that their depositional signature is likely to leave a much less well preserved trace in the rock record, compared to that of laterally-accreting channel bend deposits. We, therefore, conclude that previous studies may have under-appreciated the role of knickpoints in channel cut, maintenance and fill.

## CRediT authorship contribution statement

**Zaki Zulkifli:** Writing – review & editing, Formal analysis. **Michael A. Clare:** Writing – review & editing, Supervision. **Maarten Heijnen:** Data curation. **D . Gwyn Lintern:** Data curation. **Cooper Stacey:** Data curation. **Peter J. Talling:** Writing – review & editing, Data curation. **Matthieu J.B. Cartigny:** Writing – review & editing, Data curation. **Timothy A. Minshull:** Writing – original draft. **Hector Marin Moreno:** Writing – original draft. **Jeffrey Peakall:** Writing – review & editing, Writing – original draft. **Stephen Darby:** Writing – review & editing, Writing – original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Supplementary materials

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