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Initiation and evolution of knickpoints and their role in cut-and-fill processes in active submarine channels

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ABSTRACT

Submarine channels are the main conduits and intermediate stores for sediment transport into the deep sea, including organics, pollutants, and microplastics. Key drivers of morphological change in channels are upstream-migrating knickpoints whose initiation has typically been linked to episodic processes such as avulsion, bend cutoff, and tectonics. The initiation of knickpoints in submarine channels has never been described, and questions remain about their evolution. Sedimentary and flow processes enabling the maintenance of such features in non-lithified substrates are also poorly documented. Repeated high-resolution multibeam bathymetry between 2012 and 2018 in the Capbreton submarine canyon (southeastern Bay of Biscay, offshore France) demonstrates that knickpoints can initiate autogenically at meander bends over annual to multi-annual time scales. Partial channel clogging at tight bends is shown to predate the development of new knickpoints. We describe this initiation process and show a detailed morphological evolution of knickpoints over time. The gradients of knickpoint headwalls are sustained and can grow over time as they migrate through headward erosion. This morphology, associated plunge pools, and/or development of enhanced downstream erosion are linked herein to the formation and maintenance of hydraulic jumps. These insights of autogenically driven, temporally high-frequency knickpoints reveal that cut-and-fill cycles with depths of multiple meters can be the norm in submarine systems.

INTRODUCTION

Knickpoints are defined as steep steps in channel gradients (Gardner, 1983). They are key drivers of morphological change in submarine channels through controlling phases of channel incision and fill, the formation of terraces, and the development of channel-deposit remnants (Heiniö and Davies, 2007; Paull et al., 2011; Turmel et al., 2015; Gales et al., 2019). Knickpoint initiation has been linked to channel avulsion (Deptuck et al., 2007), bend cutoff (Sylvester and Covault, 2016), and tectonics (Heiniö and Davies, 2007), however recently, study of an active submarine channel in British Columbia (Canada) has suggested that knickpoints might be internally generated within channels (Heijnen et al., 2020). Yet we still know surprisingly little about the initiation and evolution of these features. There are key questions on the time scales over which knickpoints form, how they maintain their form in non-lithified substrates, the nature and variability of the flow above them, and consequently their overall influence on sediment transport and deposition.

Knickpoint initiation has never been observed in a submarine channel, and the temporal resolution provided by digital elevation models (DEMs) has not allowed the development of knickpoints to be observed in sufficient detail to understand their temporal evolution and associated flow processes. Repeated bathymetric surveys in the Capbreton submarine canyon (southeastern Bay of Biscay, offshore France) highlight morphological changes over the last two decades characterized by upstream knickpoint migration of several hundred meters per year. The surveys were close enough in time to provide a detailed evolution of knickpoints, show how such features of several-meters relief are maintained, and enable flow conditions to be inferred. This study shows how knickpoints autogenically initiate and establish a relation with short-time-scale processes (multiannual to annual, seasonal, or punctual events such as storms) rather than with long-term processes such as bend cutoff and avulsion (auto- or allogenic) or tectonics (allogenic).

SETTING AND DATA

Initiated 50–40 m.y. ago (Ferrer et al., 2008), the Capbreton submarine canyon lies 300 m offshore at −10 m (relative to sea level) and extends to −3000 m in the southeastern Bay of Biscay (Fig. 1A). At present, it is sediment fed by a southward longshore drift (Mazières et al., 2014). Its former associated river, the Adour, was diverted 15 km southward in 1578 CE (Klingebiel and Legigan, 1978). Water column monitoring by current meters and sediment traps have shown that sediment is transported downcanyon (Mulder et al., 2001; Gaudin et al., 2006; Brocheray et al., 2014) by two types of currents: internal tides and low-energy turbidity currents, both ranging from 0.2 to 0.3 m/s. (Mulder et al., 2012). Sediment archives evidence recent turbiditic flows with yearly to decadal recurrence for 150 km along the canyon over past 2 k.y. (Mulder et al., 2001; Gaudin et al., 2006; Brocheray et al., 2014).

Guiastrennec-Faugas et al. (2020) described as many as 80 knickpoints on the upper canyon floor (−10 to −320 m), migrating upstream at rates of 10 m/yr to 1200 m/yr. Here we focus on knickpoint initiation and evolution in three meanders: two (M1 and M2) in the upper canyon, at −260 and −300 m (9 and 11 km from the head, along-thalweg distance; Figs. 1, 2A, and 2B), and one (M3) at −1400 m (90 km from the head; Fig. 1). Five multibeam bathymetric surveys (hull-mounted EM2040 multibeam echosounder [Kongsberg Maritime]; grid resolution of 5 m) were carried out in the spring or summer of 2012, 2013, 2015, 2016, and 2018 over the upper canyon. Real-time kinematic GPS was used for the positioning with a horizontal

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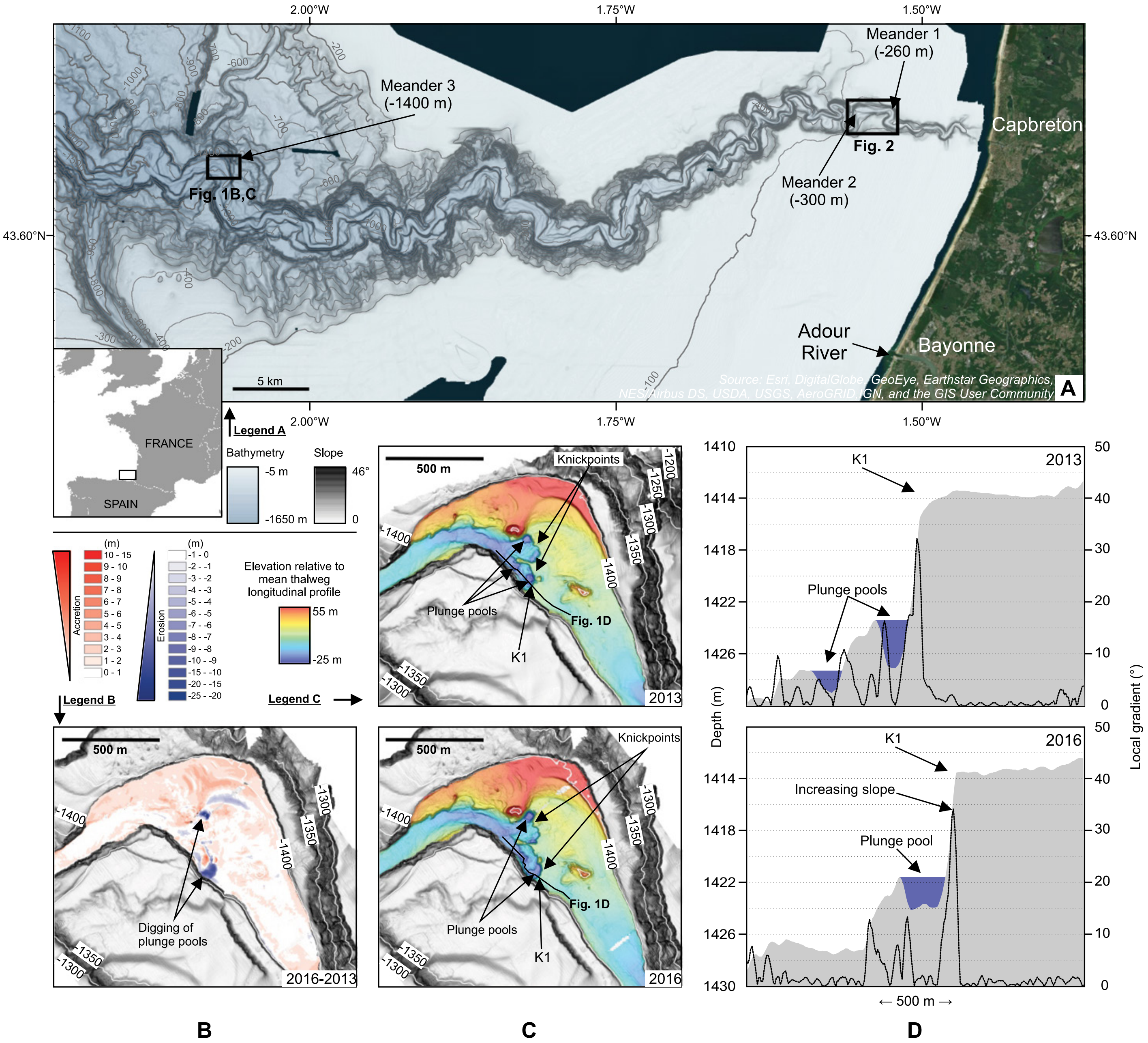

Figure 1. (A) Location of study area in the Bay of Biscay. (B–D) Meander M3 evolution between 2013 and 2016 CE: (B) Elevation change between 2013 and 2016, suggesting erosion and deposition. (C) Elevation relative to mean thalweg longitudinal profile. (D) Longitudinal profile of knickpoint K1 (gray; see C for location); black line shows along-profile slope magnitude; blue area highlights plunge pools.

resolution of 0.01 m, a vertical resolution of 0.02 m, and vertical precision of <0.2% of the water depth. Tide corrections were made using a tide prediction algorithm from SHOM (Service Hydrographique et Océanographique de la Marine; Brest, France). Statistics (Guiastrennec-Faugas et al., 2020) indicate an inter-survey bias of just 4 cm with variability of ±17 cm. Two multibeam bathymetric surveys (autonomous underwater vehicle–mounted EM2040, grid resolution of 2 m) were also undertaken in 2013 and 2016 in the lower canyon, with positioning resolution of <6 m and vertical precision of <0.5% of the water depth. Inter-survey positioning was manually performed based on a nearby area of relatively immobile seabed (Gaillot, 2016).

RESULTS

Time-lapse bathymetry (Figs. 1B, 1C, 2A, and 2B) shows upstream-migrating knickpoints in both the shallow (from −260 to −300 m) and deep (−1400 m) parts. Their evolution is controlled by headward erosion, and constrained by erosion just downstream of the knickpoint and deposition further downstream (Figs. 1B and 2A). From 2013 to 2016, knickpoint migration was 706 m/yr in the shallow part and 190 m/yr in the deep part. Knickpoint heights reach 14 m in the deep part and 7 m in the shallow part; plunge pools as deep as 10 m and <1 m, respectively, can be observed at the knickpoint bases. (Figs. 1B, 1C, 1D, and 2C). Straight sections reveal that knickpoint headwall slopes constantly increased or remained constant: between 2013 and 2018, the headwall slope of knickpoint K1 (meander M3; Fig. 1C) gradually increased from 32° to 34° (Fig. 1D), and that of knickpoint K2 (meanders M1 and M2; Fig. 2B) increased from 5° to 10° (Fig. 2C).

In meander M2 (bend angle ~90°), between 2012 and 2013, the channel became partially

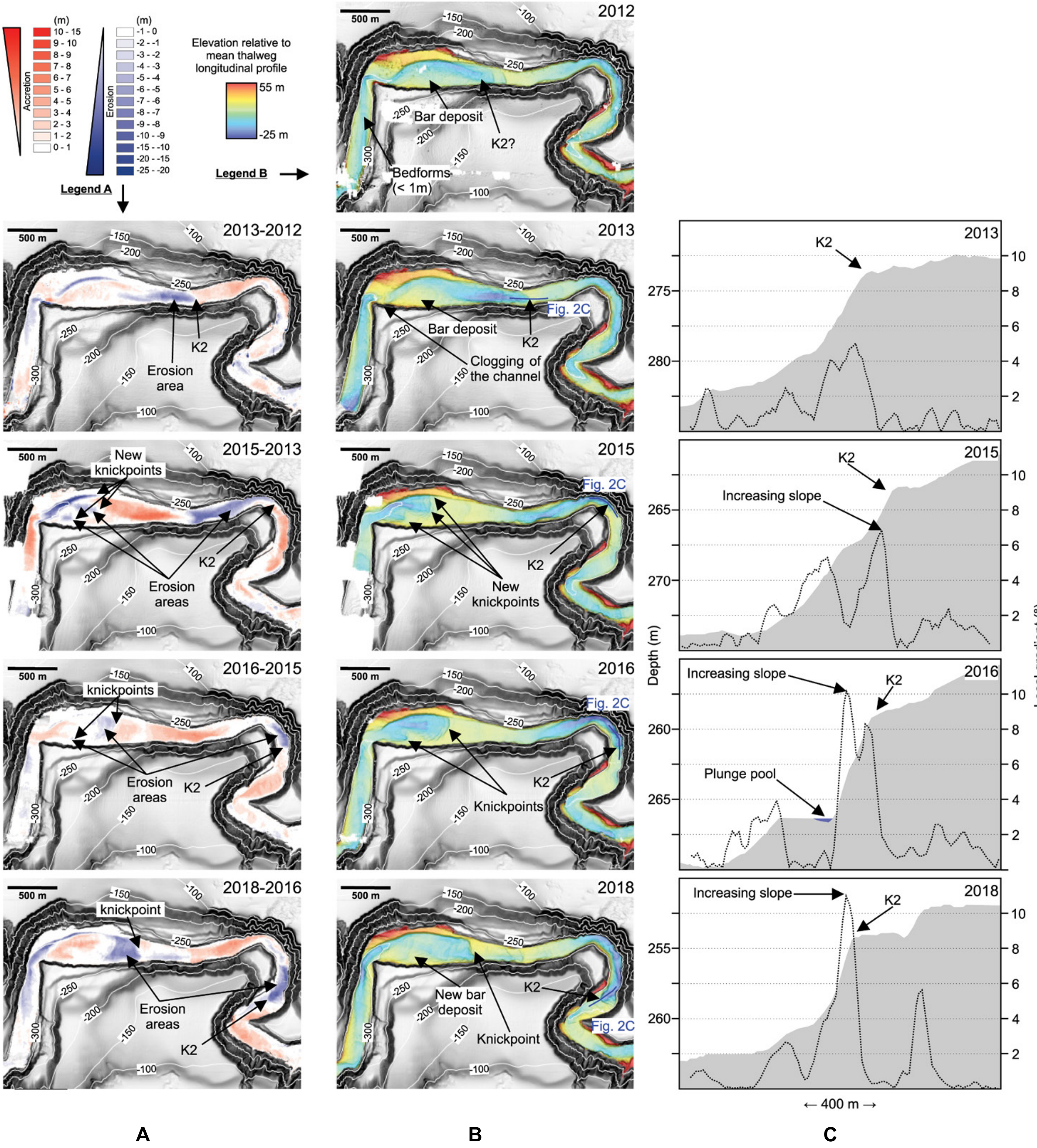

Figure 2. Evolution of meanders M1 and M2 (locations in Fig. 1A) through years 2012, 2013, 2015, 2016, and 2018 CE, highlighting knickpoint K2; see Figures 1B–1D for explanation.

blocked at the bend apex by bar deposits, leading to the upstream infilling and clogging of the channel (Fig. 2B). Three new knickpoints were observed in 2015 (Fig. 2B) and appear to have been initiated within the meander and were not connected to any other previously present knickpoint downstream of meander M2. In the 2012 DEM, morphological features with vertical relief <1 m and slopes <5° are observed downstream of the meander limb but are apparently not genetically related to any knickpoints upstream (Figs. 2A and 2B).

The evolving meander morphology was characterized by a net accumulation of sediment of ~2.9×10^5 m^3/yr (~3.54×10^5 m^3/yr erosion and ~6.44×10^5 m^3/yr accumulation over ~0.41 and ~0.64 km^2 respectively) between −300 and −260 m (meanders M1 and M2; Fig. 2A) and

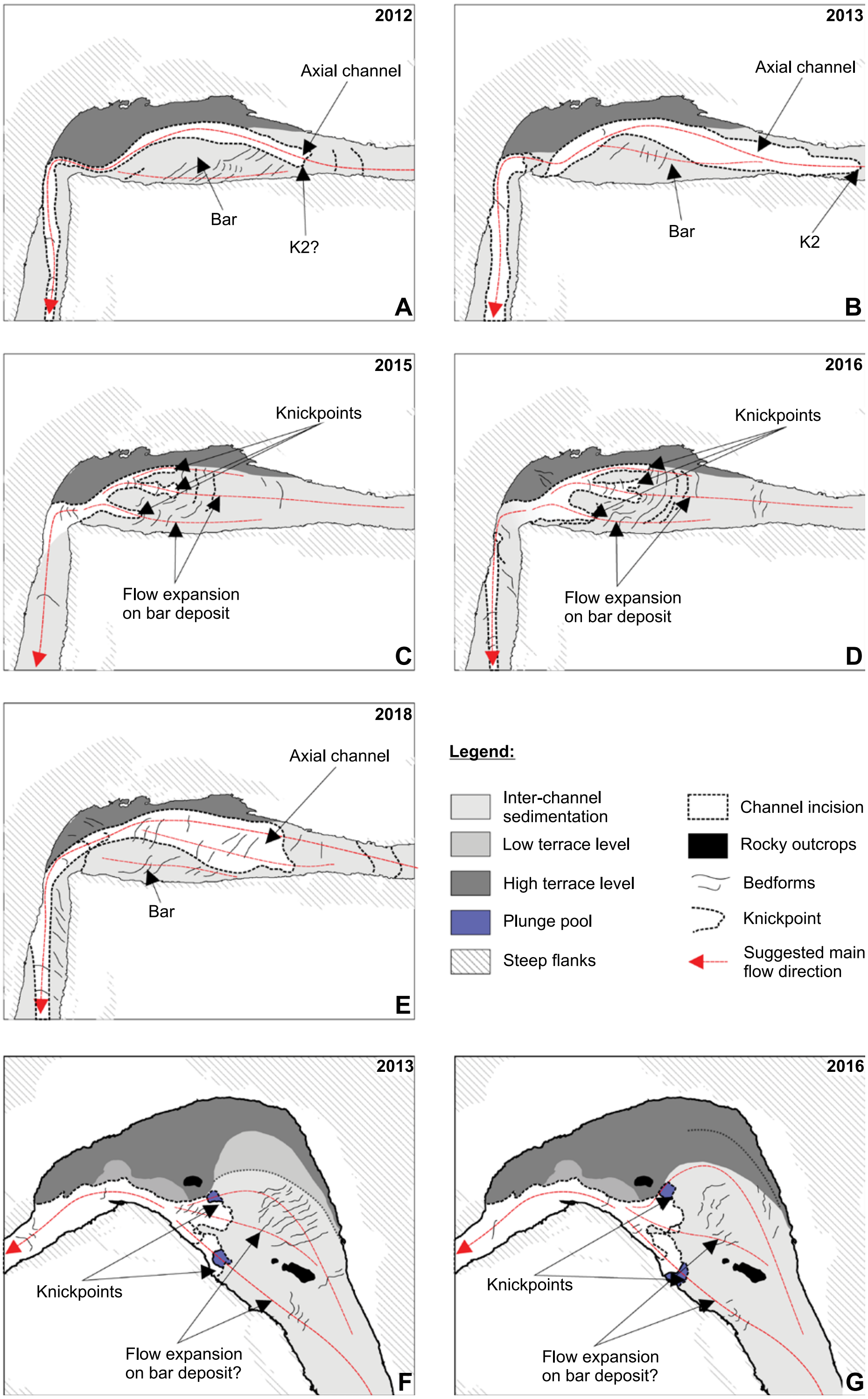

Figure 3. Knickpoint initiation on a bar deposit in a meander bend based on cases of meanders M2 (A–E) and M3 (F,G). (A,B) In meander M2, bar expansion leads to clogging of the channel, shallowing the upstream meander limb. (C,D) Backstepping erosion of the bar and knickpoint upstream migration in the form of three chute channels. (E) Erosion on the bar and knickpoint migration continues along the canyon thalweg. (F,G) Meander M3 presents a shallow upstream meander limb and the occurrence of knickpoints and chute channels.

~1.83×10^5 m^3/yr (~0.43×10^5 m^3/yr erosion and ~2.26×10^5 m^3/yr accumulation over ~0.09 and ~0.52 km^2 respectively) at −1400 m (meander M3; Fig. 1B). To allow for the different surface areas, volumes have been converted to vertical movement rates (divided by their associated area mentioned above: $m^3/yr/m^2 \rightarrow m/yr$; i.e., $[6.44 \times 10^5\ m^3/yr] / [0.64\ km^2] = 1.01\ m/yr$) to obtain +1.01 and –0.87 m/yr upstream and +0.44 and –0.50 m/yr downstream. Knickpoint migration rate and budget sediment accumulation are higher in the two shallower meanders (M1 and M2) than in the deepest meander (M3).

DISCUSSION

Knickpoint Initiation

We interpret these morphologic changes as showing knickpoints initiating at meanders with acute angles prone to point-bar sediment accumulation in the channel. Previous flume work revealed that high bend angles allow sediment to deposit just upstream of the bend apex, such as in fluvial point bars (Peakall et al., 2007). We observe repetition of two knickpoints and bars along the channel (Fig. 2), with as many as nine repetitions in the adjacent canyon (Guiastrennec-Faugas et al., 2020). The sediment eroded by knickpoint upstream migration is mobilized and bypasses down system, and bar formation occurs downstream (Fig. 2B). At the sharp bend, bar formation is enhanced, as observed in fluvial environments. At this point, we assume that the clogging of the channel (i.e., meander M2; Figs. 3A and 3B) confines the flow and increases tortuosity of flow around the bend, spreading and/or focusing flow onto the bar. As the flow reconnects with the deeper channel downstream, it leads to backstepping erosion of the point-bar deposit in the form of three chute channels (Figs. 3C and 3D). Flow thickness reduces over the point bar, potentially leading to supercritical flow (Froude number >1). At the downstream end of the bar, flow then undergoes rapid deepening as it reconnects with the deeper main channel, in which case the flow likely becomes subcritical, and a hydraulic jump may be generated at the transition. The bar also laterally confines the thalweg, likely inducing flow acceleration and therefore promoting supercritical conditions, and hence the thalweg might be expected to develop chute channels. However, in this case, a topographic step (bar-thalweg transition) with its associated gradient appears to be needed to create the flow conditions required to initiate knickpoints.

Meanders M2 and M3 each present a shallow upstream meander limb, compared to downstream of the bend apex. These similar morphologies combined with the occurrence of chute channels (Figs. 2C, 2D, 3F, and 3G) suggest similar processes in both meanders. In M1, with a bend angle of ~160°, yearly time-lapse morphology reveals that a point bar did not develop, illustrating the likely different flow conditions associated with large bend angles.

In our study, the cut-and-fill behavior related to knickpoints takes place without involvement of major external factors, such as tectonics or avulsion. No major slump scars are evidenced on the canyon flanks (Guiastrennec-Faugas et al., 2020). Neither water depth nor the rate of sediment accumulation seems to control knickpoint initiation. Thus, it is the combination of a sharp bend and sediment accumulation supplied from the process of knickpoint migration (erosion and then deposition) that leads to the autogenic initiation of knickpoints. As new knickpoints migrate upstream, this results in repeated channel clogging (bar formation) and the subsequent development of a new knickpoint. Essentially, each knickpoint generates the next one.

Point-bar development and bend cutoff (Sylvester and Covault, 2016) are both autogenic processes for the generation of knickpoints, associated with channel evolution and migration. Nevertheless, evolution in the Capbreton submarine canyon is observed in an already established canyon and migration affects only the axial channel, while in the study of Sylvester and Covault (2016), knickpoint initiation is linked to migration of the entire channel.

Knickpoint Evolution and Flow Conditions

Erosion initiated on the point bar (meander M2) continues along the canyon thalweg in the form of knickpoint upstream migration (i.e., knickpoint K2 in Fig. 2; Fig. 3E). Morphology time lapse confirms that incipient knickpoints are gentle steps that become steeper as they migrate upstream (Fig. 2).

The observation of plunge pools is evidence of the presence of hydraulic jumps (Komar, 1971; Bourget et al., 2011; Mulder et al., 2019). Hydraulic jumps imply a shift from supercritical to subcritical flow conditions, and thus imply that such flow conditions may be related to knickpoints (Fig. 4). Previous laboratory experiments on non-indurated sediments confirm highly variable flow conditions in the vicinity of submarine knickpoints (Toniolo and Cantelli, 2007). Measurements of subaqueous hydraulic jumps over scours in the Black Sea (Dorrell et al., 2016) show flow acceleration on the headwall. The hydraulic jump would lead to erosion at the base of the slope, resulting in an area of nondeposition and/or erosion representing sediment mobilized and/or excavated by the hydraulic jump just downstream of the knickpoints (Mitchell, 2006). In the Capbreton submarine canyon, plunge pools are not systematically observed downstream of knickpoints, but areas of erosion are. In either case, knickpoints develop where depth suddenly increases (bar-thalweg transition), which may encourage a hydraulic jump.

Two cores sampled in the study area at −301 m (thalweg) and −251 m (terrace) record very coarse sand and gravel in the thalweg and a continuous silty-clay deposit on the terrace 50 m above the thalweg (Duros et al., 2017). A third core located upstream on a terrace, at −214 m and 13 m above the thalweg, sampled medium-sand turbidites (Guiastrennec-Faugas et al., 2020). The grain-size variations suggest that flows are highly stratified, with the sand-rich component at least 13 m thick but <50 m. The knickpoint relief (as much as 7 m) is therefore relatively small compared to total estimated flow thickness, however the stratified nature of the flow and the coupling of velocity and sediment mean that momentum is highly concentrated toward the base of stratified sand-rich turbidity currents (Wells and Dorrell, 2021). The basal parts would thus be expected to respond to the increased gradients across knickpoints (Dorrell et al., 2016).

Erosion areas, including plunge pools, are crucial to the sustainability of knickpoints and their migration, and directly depend on flow dynamics. Erosion against the headwall maintains a local steep slope. In turn, the steep gradient promotes hydraulic jumps at that location, which propagate the knickpoint structure (Fig. 4). Erosion on top of the headwall could be related either to flow characteristics (erosion at the base of flow) or to a collapse as a consequence of erosion at the base of the headwall as suggested by Heijnen et al. (2020), or both.

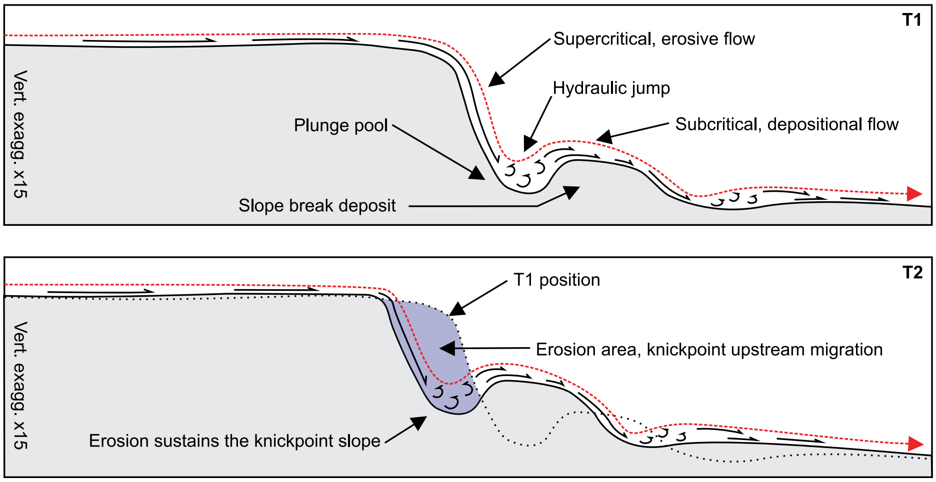

Figure 4. Schematic longitudinal sketch of flow conditions and the temporal evolution of a knickpoint and associated plunge pool between times T1 and T2. Knickpoint upstream migration occurs by erosion of the headwall. Erosion at the base of the headwall sustains knickpoint slope while moving sediment further downdip, where sedimentation forms a new bar. Vert. exagg.—vertical exaggeration.

At −1400 m (meander M3), the lower velocity of knickpoint migration and sediment accumulation budget in comparison to the two shallower meanders suggest less-frequent flows. This is consistent with observations made in Monterey Canyon (offshore California, USA; Stevens et al., 2014) where turbidity current activity (number and intensity) decreases with the distance from the source. The type and size of turbidity currents (volume and sediment concentration with regard to channel-floor dimension) could determine the occurrence of plunge pools and the sustainability and migration of knickpoints. The highest knickpoints and the deepest plunge pools are found in the deeper section and exhibit slower upstream migration, perhaps related to the lower positive sediment budget, whose consequence would be a better morphological expression and preservation of erosional processes and features.

CONCLUSION

Using high-resolution repeated bathymetry from the Capbreton submarine canyon, we identify autogenic initiation of knickpoints for the first time, reveal the morphological evolution of knickpoints, and link the morphology to the formation and maintenance of hydraulic jumps. The combination of sediment supply and meander morphology leading to bar deposition and channel clogging is observed to be among the possible prerequisites for knickpoint initiation. These data reveal that knickpoints in non-lithified substrates can initiate and develop autogenically on annual, and maybe seasonal and event, time scales, orders of magnitude shorter than the periodicity envisaged from mechanisms such as avulsion, tectonism, and bend cutoff. We demonstrate that cut-and-fill cycles with depths of multiple meters, driven by high-frequency autogenic knickpoints, can be the norm in submarine systems capable of supporting flows with velocities sufficient to create hydraulic jumps. Thus, the observation of large-scale (multiple-meter) erosion surfaces in channelized submarine systems in the rock record can be autogenic and geologically instantaneous and do not imply changes in external controls nor temporal scales beyond multiannual.

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