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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 cut-off 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 2012-2018 in the Capbreton submarine canyon demonstrates that knickpoints can initiate autogenically at meander bends, over annual to pluri-annual timescales. Partial channel clogging at tight bends is shown to predate the development of new knickpoints. We describe this initiation process and show 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 multi-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; Gales et al., 2019; Turmel et al., 2015; Paull et al., 2011). Knickpoint initiation has been linked to channel avulsion (Deptuck et al., 2007), bend cut-off (Sylvester and Covault, 2016) and tectonics (Heiniö and Davies, 2007), however recently, study of an active submarine channel in British Columbia 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 timescales 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 (CSC) highlight morphological changes over the last 2 decades characterized by upstream knickpoint migration of several 100 m/yr. 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 (pluri-annual to annual, seasonal or punctual events such as storms) rather than with long-term processes such as bend cut-off and avulsion (auto- or allogenic) or tectonics (allogenic).

SETTINGS AND DATA

Initiated 50-40 My ago (Ferrer et al., 2008), the CSC lies 300 m offshore at -10 m and extends to -3000 m in the SE of the Bay of Biscay (Fig. 1A). The CSC is nowadays 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 2 types of currents: internal tide and low energy turbidity currents ranging from 0.2–0.3 m/s (Mulder et al., 2012). Sediment archives state of recent turbiditic flows with yearly to decadal recurrence over 150 km along the CSC over last 2 kyrs (Mulder et al., 2001; Gaudin et al., 2006; Brocheray et al., 2014). Guiastrennec et al. (2020) described up to 80 knickpoints on the upper CSC 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; 2 (M1 & M2) in the upper CSC, at -260 and -300 m (9 & 11 km from the head, along thalweg distance; Figs. 1, 2A, B), and 1 (M3) at -1400 m (90 km from the head; Fig. 1). Five multibeam bathymetric surveys (hull mounted EM2040; grid resolution of 5 m) were carried out in spring or summer of 2012, 2013, 2015, 2016 and 2018 over the upper CSC. Real Time Kinematic (RTK) GPS was used for the positioning with a horizontal resolution of 0.01 m and a vertical resolution of 0.02 m; vertical precision < 0.2% of the water depth; tide corrections were made using a tide prediction algorithm from the SHOM (S*ervice Hydrographique et Océanographique de la Marine)*; statistics (Guiastrennec et al., 2020) indicate an inter survey bias of just 4 cm with variability of +/-17 cm. Surveys in the upper CSC along with 2 multibeam bathymetric surveys (AUV mounted EM240, grid resolution of 2 m) were also undertaken in 2013 and 2016 in the lower CSC. Positioning resolution < 6 m; vertical precision < 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, C, 2A, B) show upstream migrating knickpoints both in 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, 2A). From 2013 to 2016, knickpoint migration was 706 m/yr in the shallow part, and 190 m/yr in the deep part. Their heights reach 14 m in the deep part and 7 m in the shallow part. Plunge pools can be observed at their base respectively up to 10 m deep and < 1 m. (Figs. 1B, C, D, 2C). Straight sections reveal that their headwall slope constantly increased or remained constant: between 2013 and 2018 the headwall slope of knickpoint K1 (M3; Fig 1C) gradually increased from 32° to 34° (Fig. 1D) and that of knickpoint K2 (M1 & 2; Fig. 2B) from 5° to 10° (Fig. 2C).

In M2 (bend angle ~90°), between 2012 and 2013, the channel became partially blocked at the bend apex by bar deposits leading to the upstream infilling and clogging of the channel (Fig. 2B). 3 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 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, B).

The evolving meander morphology was characterized by a net accumulation of sediment of ~290k m^3/yr (~354k m^3/yr erosion and ~644k m^3/yr accumulation over respectively ~0.41 and ~0.64 km^2) between -300 and -260 m (M1 & 2; Fig. 2A) and ~183k m^3/yr (~43k m^3/yr erosion and ~226k m^3/yr accumulation over respectively ~0.09 and ~0.52 km^2) at -1400 m (M3; Fig. 1B). To allow for the different surface areas, volumes have been converted to vertical movement rates (divided by their associated area mention herein above: $m^3/yr/m^2 \rightarrow m/yr$; i.e. 644k 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 2 shallower meanders (M1 & 2) 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 point bars in rivers (Peakall et al., 2007). We observe repetition of 2 knickpoints and bars along the channel (Fig. 2), with up to 9 repetitions in the adjacent canyon (Guiastrennec et al., 2020). The sediment eroded by knickpoint upstream migration is mobilised and bypassed 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. M2; Figs. 3A, B) confines the flow and increases tortuosity of flow around the bend, spreading and/or focusing flow onto the bar. As flow reconnected with the deeper channel downstream, it led to backstepping erosion of the point bar deposit in the form of three chute channels (Figs. 3C, D). Flow thickness will have reduced over the point bar potentially leading to supercritical flow

(Froude number >1). At the downstream end of the bar, flow will then undergo rapid deepening as it reconnects with the deeper main channel, in which case the flow will likely become subcritical, and a hydraulic jump may have been 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 needed to create flow conditions required to initiate knickpoints.

M2 and M3 both 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, D, 3F, G) suggests similar processes in both meanders. In M1, with a bend angle ~160°, yearly time-lapse morphology reveals that a point bar did not develop, illustrating the likely different flow conditions associated with large bend angles.

Here, the cut and fill behavior related to knickpoints takes place without involvement of major external factors, tectonics or avulsion. No major slump scars are evidenced on the canyon flanks (Guiastrennec et al., 2020). Neither water depth, or the rate of sediment accumulation, seem 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 cut-off (Sylvester and Covault, 2016), are both autogenic processes for the generation of knickpoints, associated with channel evolution and migration. Nevertheless, evolution in the CSC is observed in an already established canyon and migration only affects 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 (M2) continues along the canyon thalweg in the form of knickpoint upstream migration (i.e. K2 on 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 can be related to knickpoints (Fig. 4). Previous laboratory experiments on non-indurated sediments (simulating river alluvial beds) confirm highly variable flow conditions in the vicinity of 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 will lead to erosion at the base of the slope resulting in an area of nondeposition/erosion representing sediment mobilized/excavated by the hydraulic jump just downstream of the knickpoints (Mitchell, 2006). In the CSC, 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) have recorded 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 et al., 2020). The grain-size variations suggest that flows are highly stratified, with the sand-rich component at least 13 m thick, but less than 50 m. The knickpoint relief (up to 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 towards the base of stratified sand-rich turbidity currents (Wells and Dorrell, 2021). The basal parts would 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 propagates the knickpoint structure (Fig. 4). Erosion on top of the headwall could either be related to flow characteristics (erosion at the base of flow), or be related to a collapse as a consequence of erosion at the base of the headwall as suggested by Heijnen et al. (2020), or both.

At -1400 m, the lower velocity of knickpoint migration and sediment accumulation budget in comparison to the 2 shallower meanders suggest less frequent flows. This is consistent with observations made in Monterey Canyon (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 CSC 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 point bar deposition and channel clogging is observed to be among the possible prerequisites for knickpoint initiation. This data reveals 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 cut-off. We demonstrate that cut and fill cycles with depths of multi-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 (multi-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 multi-annual.

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Fig. 1: (A) Location of the study area in the Bay of Biscay; (B, C, D) Meander 3 evolution between 2013 and 2016; (B) Elevation change suggesting erosion and deposition. (C) Elevation

relative to mean thalweg longitudinal profile. (D) In grey, longitudinal profile of K1; black line: along-profile slope magnitude; blue area highlights plunge pools.

Fig. 2: Meander 1 & 2 (loc. on Fig. 1A) evolution through years 2012, 2013, 2015, 2016 and 2018, parts A to C as per Figures 1B-1D.

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

Fig. 4: Schematic longitudinal sketch of flow conditions and temporal evolution of a knickpoint and associated plunge pool. Knickpoint upstream migration occurs by erosion of the headwall. Erosion at the base of the headwall sustains the knickpoint slope whilst moving sediment further downdip, where sedimentation forms a new bar.

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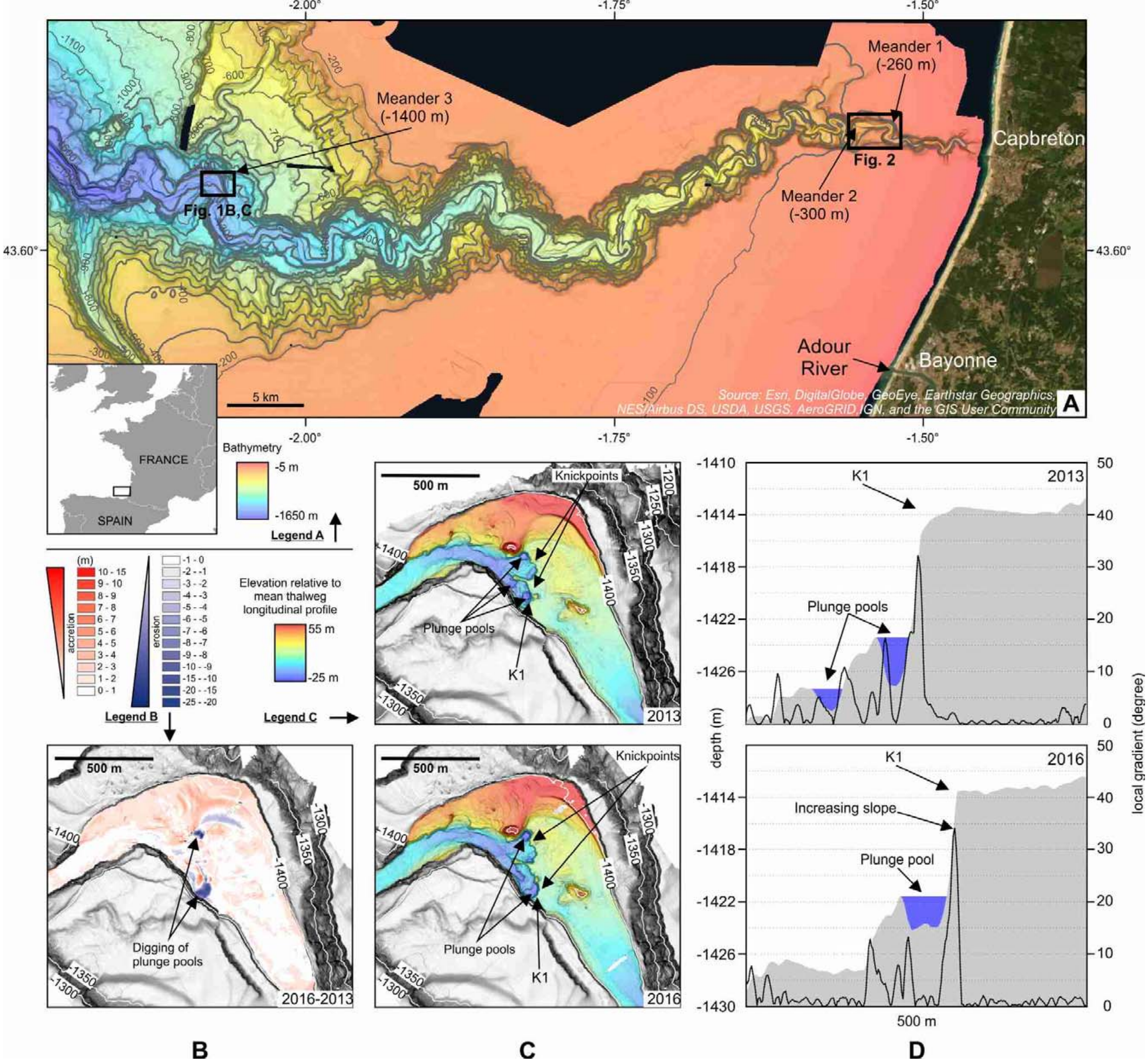
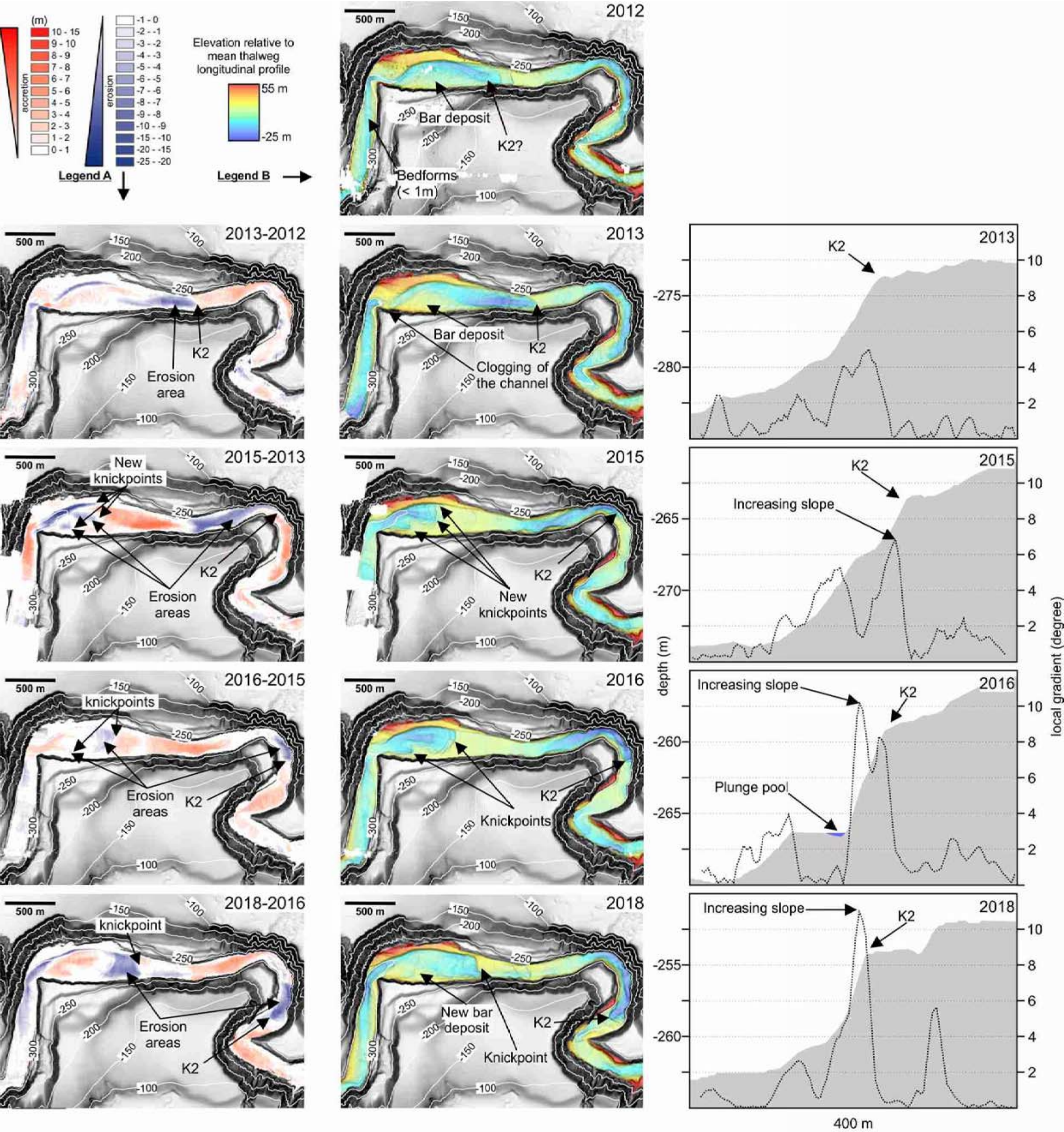
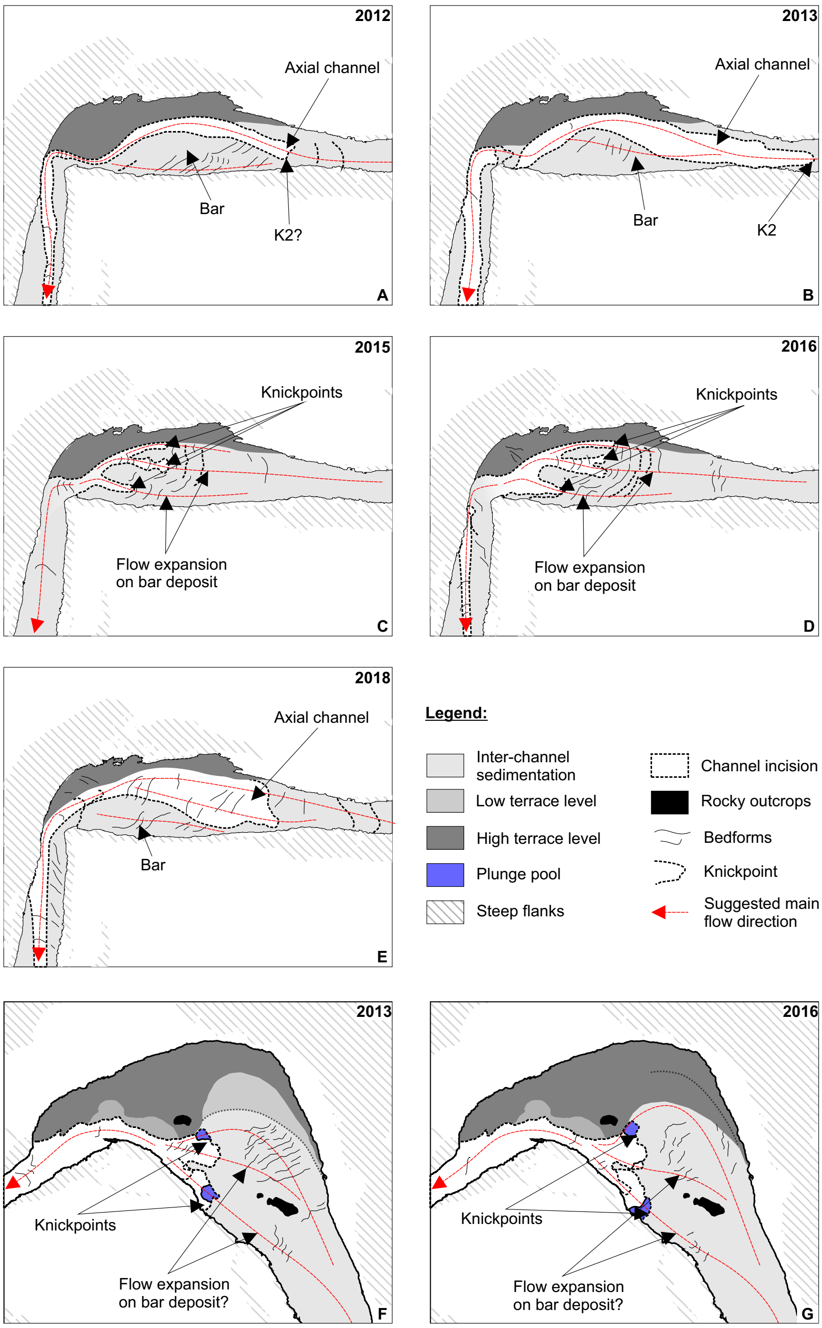
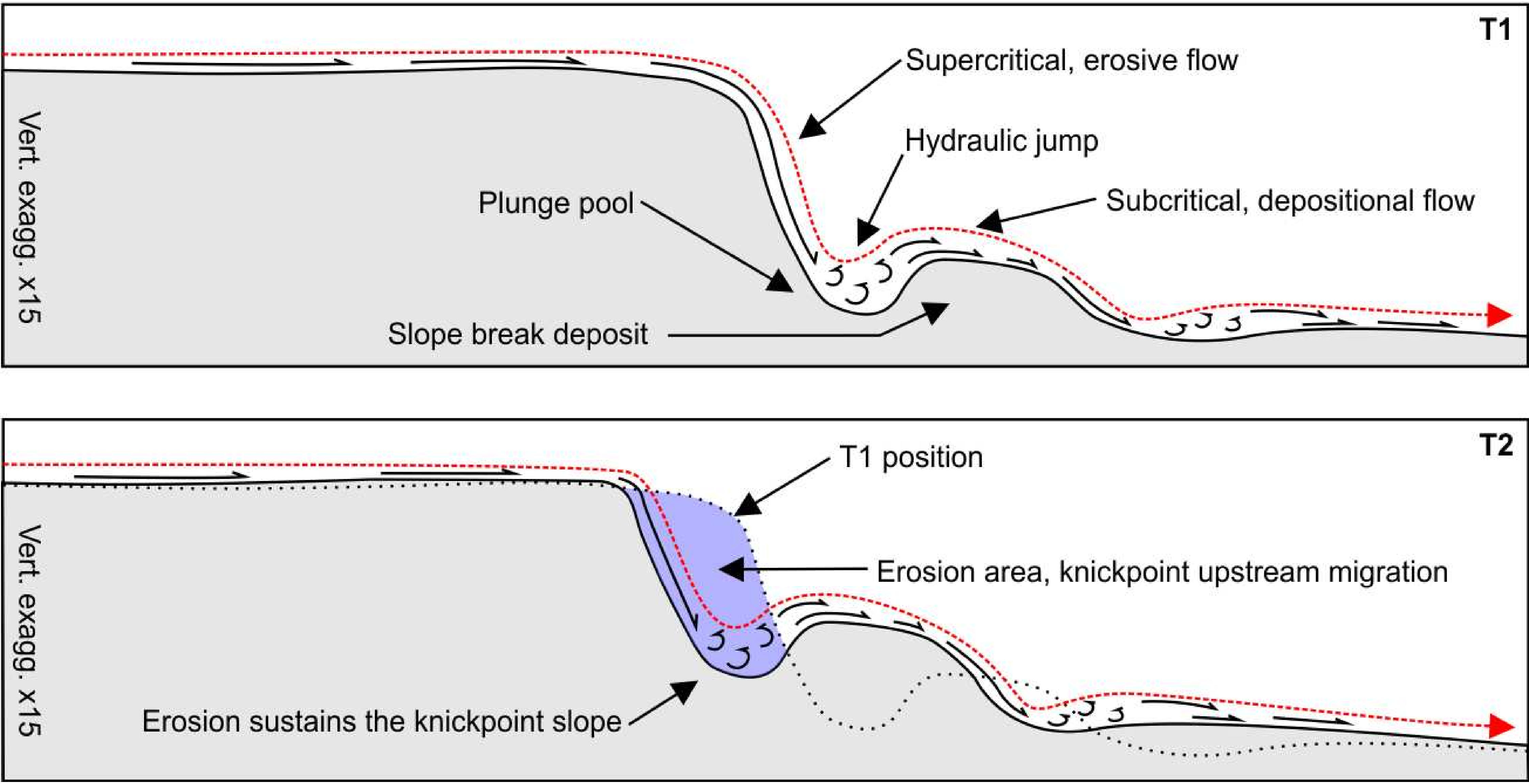


Meander 1
(-260 m)
Meander 3
(-1400 m)
Capbreton
Fig. 2
Fig. 1B,C
Meander 2
(-300 m)
Adour
River
Bayonne
5 km
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, NES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
A
FRANCE
SPAIN
Bathymetry
-5 m
-1650 m
Legend A
accretion
erosion
Legend B
Elevation relative to mean thalweg longitudinal profile
55 m
-25 m
Legend C
Knickpoints
Plunge pools
K1
2013
2016
500 m
Digging of plunge pools
2016-2013
K1
Plunge pools
Increasing slope
Plunge pool
depth (m)
local gradient (degree)
B
C
D



Legend A
accretion
erosion
(m)
Elevation relative to mean thalweg longitudinal profile
55 m
-25 m
Legend B
2012
Bar deposit
K2?
Bedforms (< 1m)
2013-2012
Erosion area
K2
2013
Bar deposit
K2
Clogging of the channel
2015-2013
New knickpoints
Erosion areas
K2
2015
New knickpoints
K2
2016-2015
knickpoints
Erosion areas
K2
2016
Knickpoints
K2
2018-2016
knickpoint
Erosion areas
K2
2018
New bar deposit
Knickpoint
K2
2013
K2
2015
K2
Increasing slope
2016
Increasing slope
K2
Plunge pool
2018
Increasing slope
K2
depth (m)
local gradient (degree)
400 m
A
B
C


2012
Axial channel
Bar
K2?
A
2013
Axial channel
Bar
K2
B
2015
Knickpoints
Flow expansion
on bar deposit
C
2016
Knickpoints
Flow expansion
on bar deposit
D
2018
Axial channel
Bar
E
Legend:
Inter-channel sedimentation
Low terrace level
High terrace level
Plunge pool
Steep flanks
Channel incision
Rocky outcrops
Bedforms
Knickpoint
Suggested main flow direction
2013
Knickpoints
Flow expansion
on bar deposit?
F
2016
Knickpoints
Flow expansion
on bar deposit?
G


T1
Supercritical, erosive flow
Hydraulic jump
Subcritical, depositional flow
Plunge pool
Slope break deposit
Vert. exagg. x15
T2
T1 position
Erosion area, knickpoint upstream migration
Erosion sustains the knickpoint slope
Vert. exagg. x15