Channel-levee evolution in combined contour current–turbidity current flows from flume-tank experiments

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ABSTRACT

Turbidity currents and contour currents are common sedimentary and oceanographic processes in deep-marine settings that affect continental margins worldwide. Their simultaneous interaction can form asymmetric and unidirectionally migrating channels, which can lead to opposite interpretations of paleocontour current direction: channels migrating against the contour current or in the direction of the contour current. In this study, we performed three-dimensional flume-tank experiments of the synchronous interaction between contour currents and turbidity currents to understand the effect of these combined currents on channel architecture and evolution. Our results show that contour currents with a velocity of 10–19 cm s⁻¹ can substantially deflect the direction of turbidity currents with a maximum velocity of 76–96 cm s⁻¹, and modify the channel-levee system architecture. A lateral and nearly stationary front formed on the levee located upstream of the contour current, reduced overspill and thus restrained the development of a levee on this side of the channel. Sediment was preferentially carried out of the channel at the flank located downstream of the contour current. An increase in contour-current velocity resulted in an increase in channel-levee asymmetry, with the development of a wider levee and more abundant bedforms downstream of the contour current. This asymmetric deposition along the channel suggests that the direction of long-term migration of the channel form should go against the direction of the contour current due to levee growth downstream of the contour current, in agreement with one of the previously proposed conceptual models.

INTRODUCTION

Turbidity currents are underwater gravity-driven flows that transport large amounts of sediment to the deep sea (Normark, 1970). They play an important role in global carbon cycling and sequestration (Galy et al., 2007), bring nutrients to deep-sea ecosystems (Khripounoff et al., 2012), transport microplastics downslope (Kane and Clare, 2019), and can pose a hazard for seafloor infrastructure (Carter et al., 2014). Moreover, their deposits can host reservoirs for hydrocarbons (Mayall et al., 2006) and can be used as archives for paleoclimatic reconstructions (Bonneau et al., 2014). Although the transfer of sediment from the continent to the deep sea through gravity flows has mainly been considered to be a downslope process, many systems show characteristics that suggest that turbidity currents and their related deposits (i.e., turbidites) can be affected by along-slope bottom currents (i.e., contour currents), resulting in the formation of asymmetric channel-levee systems (Fig. 1). Asymmetrical and unidirectionally migrating submarine channels and canyons have widely been used for paleoceanographic reconstruc-

tions (e.g., He et al., 2013). However, because the processes at the origin of these sedimentary bodies are not well understood, the interpretations of the current directions based on the deposits are disputed in literature. For instance, Fonnesu et al. (2020) suggested that channels migrate in the upstream direction of contour currents due to levee growth on the downstream side of contour currents. In contrast, Gong et al. (2018) suggested that channels migrate in the downstream direction of contour currents, and that levees mainly grow upstream of the contour current. In our study, we recorded the interplay between contour currents and turbidity currents in three-dimensional flume-tank experiments in order to gather first-order observations of how downslope and along-slope processes interact, and how contour currents may affect the geometry of channel-levee systems.

FLUME-TANK EXPERIMENTS

Experiments that simulated the simultaneous interaction between contour currents and turbidity currents were carried out in the Eurotank Flume Laboratory (Utrecht University, Netherlands), an $11 \times 6 \times 1.2$ m basin, where experiments on channel-levee systems have been successfully performed in previous studies (de Leeuw et al., 2016, 2018a, 2018b). Turbidity currents were generated by pumping a mixture of sediment and water (median grain size of 133 μm; volume concentration of sediment 17%; volume of 0.9 m³, and discharge of ~30 m³ hr⁻¹) into a preformed channel on an 11° slope. The shape and dimensions of the channel (80 cm wide and 3 cm deep) were identical to

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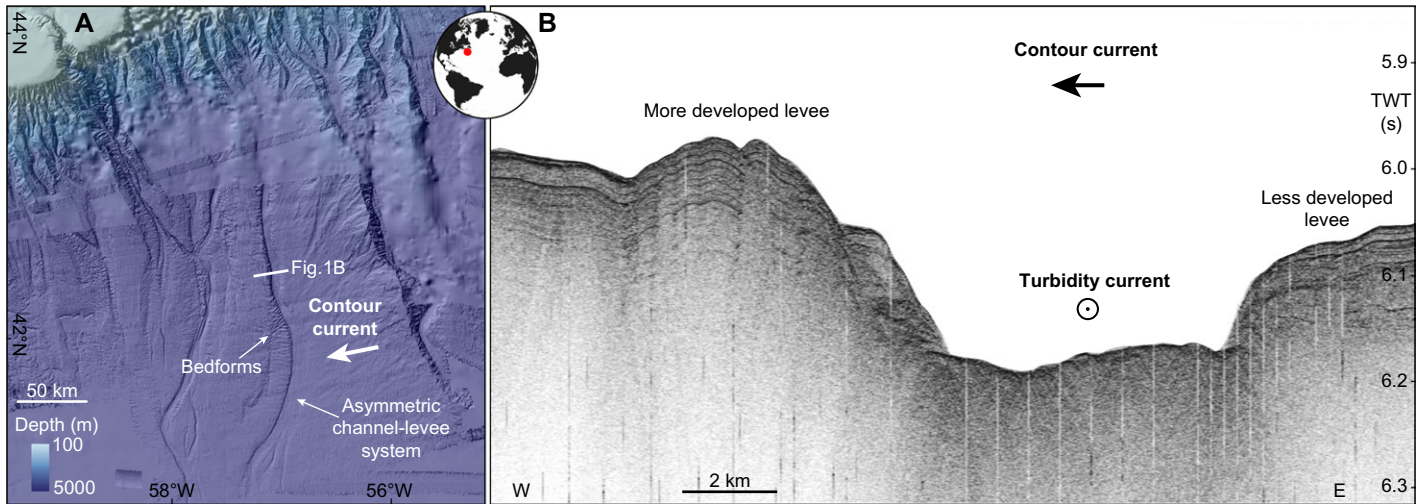
Figure 1. Multibeam bathymetry (A) and 3.5 kHz subbottom profiler image (B) of mixed turbidite-contourite system offshore eastern Canada (location indicated with red dot in inset), characterized by an asymmetric channel-levee system and an asymmetric distribution of bedforms. TWT—two-way traveltime.

those of Leeuw et al.'s (2018b) run 5. This channel form was chosen because a significant part of the turbidity current elevated above the channel flanks during the experiments and would have thus interacted with the contour current. In our study, we implemented an array of pumps that generated water circulation in the basin, and contour currents along the slope (Fig. DR1 in the GSA Data Repository[1]). In our first experiment, the turbidity current flowed through standing water without contour currents. Then, three more experiments were carried out maintaining a similar preparation of the turbidity current, but with three different contour-current velocities (10, 14, and 19 cm s^{-1}), using, respectively, 1, 2, and 3 pumps (Fig. DR2). The velocity of the contour currents and turbidity currents was measured using a Signal Processing SA (https://www.signal-processing.com) UDOP 4000 velocimeter, which was located in the middle of the slope in the channel thalweg. This velocimeter measured time series of velocity profiles of the across- and along-slope velocity component (Figs. DR1 and DR3).

MODIFICATION OF TURBIDITY CURRENT STRUCTURE BY CONTOUR CURRENTS

The turbidity current flowing in standing water overspilled symmetrically over both flanks of the channel (Fig. 2A). In contrast, overspilling was asymmetric in the presence of a contour current. Underwater images of the experiment clearly show that overspill occurred mainly downstream of the contour current (Fig. 2B).

Upstream of the contour current, overspill of the turbidity current was blocked by the opposing contour current, generating a stationary lateral front (Fig. 2). Part of the sediment carried by the turbidity current was advected by the contour current and transported in suspension along slope (Fig. 2B).

The contour currents substantially modified the flow properties of turbidity currents, especially the time-averaged downslope velocity and

the direction of the flow (Fig. 3). In the experiment with the turbidity current in standing water, the time-averaged downslope velocity maximum was 87 cm s^{-1}. In the experiments with contour currents of 10 and 14 cm s^{-1}, the velocity maximum increased to 96 cm s^{-1}, whereas with the strongest contour current (19 cm s^{-1}), it decreased to 76 cm s^{-1}. The ratio of contour-current speed and maximum downslope turbidity-current velocity thus increased from 0.10 to
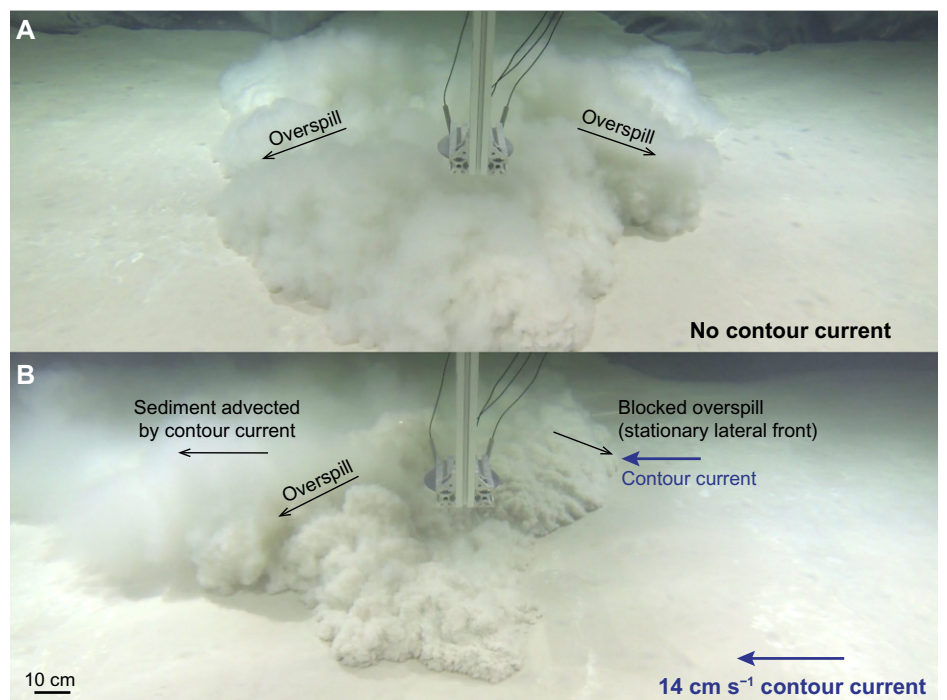

Figure 2. Single frames from video of a turbidity current during two experiments: a turbidity current flowing in standing water without a contour current (A); and a turbidity current interacting with a contour current of 14 cm s^{-1} (B). The UDOP 4000 velocimeter, used to measure velocity profiles during experiments, can be observed in the center of the images. Full video is available in the Data Repository (see footnote 1).
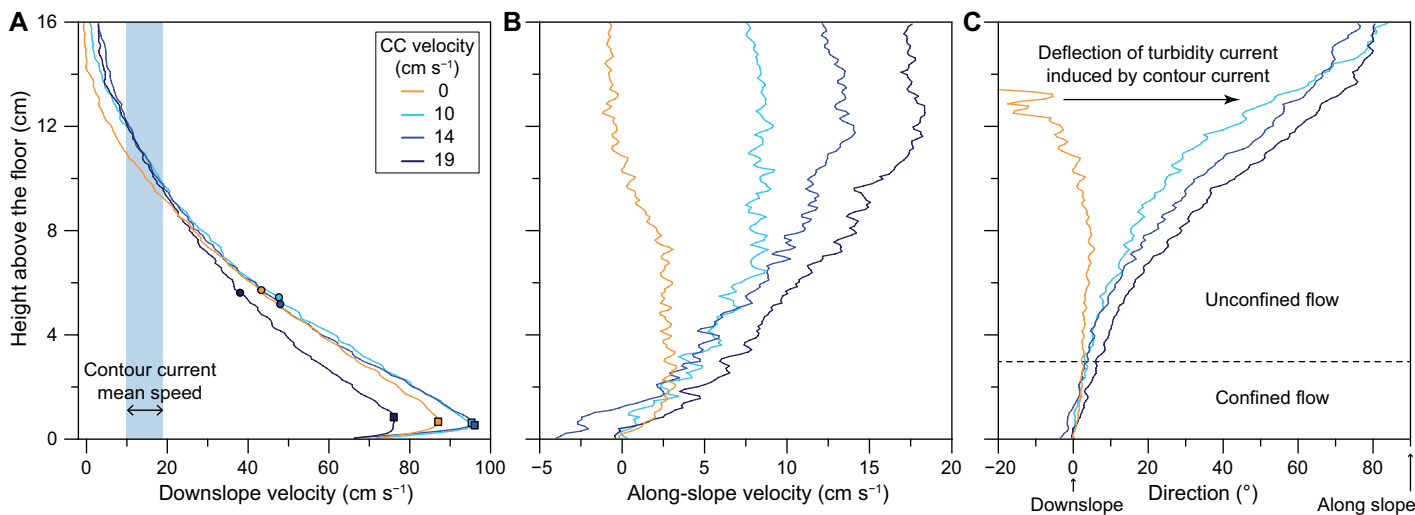
Figure 3. (A) Time-averaged downslope velocity profile for all experiments. Squares represent maximum velocity of turbidity currents, and circles represent flow thickness, which is here defined as the height at which the velocity is half the velocity maximum. Vertical light-blue band indicates the range of mean contour current speed used in the experiments (10–19 cm s⁻¹). (B) Time-averaged, along-slope velocity profile for all experiments. (C) Time-averaged direction of turbidity current for each experiment. CC—contour current.

0.15 and to 0.25 in the three contour current experiments. The mean flow thickness, here calculated as the height at which the velocity is half the velocity maximum, was similar in all the experiments, ranging between 5.2 and 5.7 cm (Fig. 3A). The along-slope velocity component of the turbidity current in standing water was 2.5 cm s⁻¹, which is a small fraction of the downslope velocity component (87 cm s⁻¹).

With introduction of a contour current, the along-slope velocity component of the turbidity current increased with the velocity of the contour current (Fig. 3B). The current profile resulting from the combination of the contour current and the turbidity current had a spiral structure; i.e., the direction of the flow changed with the distance from the floor, turning progressively along slope (downstream of the contour current). This change in direction was especially obvious above 3 cm, where the flow was unconfined above the channel (Fig. 3C).

DEVELOPMENT OF AN ASYMMETRIC CHANNEL-LEVEE SYSTEM

The changes in the properties of turbidity currents induced by the simultaneous interaction with contour currents are reflected in the resulting deposits (Fig. 4). Deposition maps were obtained from differential topographies measured with a laser scanner before and after the experiments (Fig. DR1). In the experiment in standing water, symmetric levees with bedforms (ripples at this scale) formed on both sides of the channel, with their crests oriented at an angle of 30°–45° with respect to the channel (Fig. 4A). In contrast, levees became more asymmetric with increasing contour-current velocity, due to an enhancement in sediment accumulation on the levee downstream of the contour current. Upstream of the contour current, the levee

became narrower and bedforms progressively disappeared, whereas downstream of the contour current, the levees became wider and the bedforms formed over a larger area (Fig. 4). The effect of the contour currents was especially marked in the levee width (Fig. DR4F). The faster the contour current flowed, the narrower the levee was upstream of the contour current, and the wider it was downstream of the contour current. However, the effect of the contour currents was less marked in the levee height, which may have been controlled by other secondary processes and not directly by the contour currents (Fig. 4; Fig. DR4E).

The asymmetry observed in the deposits agrees with velocity measurements and observations in underwater videos, which showed a deviation of the entire turbidity current in the direction of the contour current. Changes in deposition thickness within the channel and in the position of the lobes are also observed in the experiments. With weak contour currents (10 cm s⁻¹), less sediment accumulated within the channel, and the lobe was located farther downslope compared to the experiment in standing water. High contour-current velocities resulted in a progressive enhancement of the channel infill and a reduction of the runout distance (Fig. 4).

DISCUSSION AND CONCLUSION
Comparison with Natural Mixed Turbidite-Contourite Systems

Turbidity currents are energetic flows with velocities ranging from few decimeters to a few meters per second (e.g., Azpiroz-Zabala et al., 2017). The velocities of contour currents along continental margins, however, are typically in a narrower range, of few tens of centimeters per second (Shanmugam et al., 1993). We consider the ratio between along-

slope contour-current velocity and the maximum downslope velocity of turbidity currents as the best scaling ratio for the relative strength of contour currents and turbidity currents. In our experiments, the velocity of the contour current was between 10% and 25% of the maximum velocity of the turbidity current. The modest interactions observed in the experiment with a 10 cm s⁻¹ contour current could thus scale to natural contour currents of 0.2 m s⁻¹ and turbidity currents of 2 m s⁻¹, or to weaker contour currents and slower turbidity currents. The strong interaction observed in the experiment with a 19 cm s⁻¹ contour current could scale to the effect of a 0.2 m s⁻¹ contour current on a turbidity current traveling at <1 m s⁻¹, or alternatively to a stronger contour current affecting a faster turbidity current. These projected ranges of scaled turbidity-current velocities illustrate that the interactions observed in this study can be expected to occur for the full range of recorded turbidity-current velocities (Khripounoff et al., 2012; Hughes Clarke et al., 2016; Azpiroz-Zabala et al., 2017), with the exception of highly energetic turbidity currents in steep proximal canyons (Paull et al., 2018).

The channel-levee architecture resulting from the simultaneous interaction of turbidity currents with contour currents in our experiments is similar to that of natural mixed turbidite-contourite systems, with a more developed levee, and more abundant bedforms, downstream of the contour currents (Fig. 1; Normandeau et al., 2019; Fonnesu et al., 2020). We conclude that sedimentation is enhanced in the levee located downstream of the contour current, probably resulting in a channel migrating upstream of the contour current, as suggested for mixed systems in northern Mozambique (Fonnesu et al., 2020) and in Nova
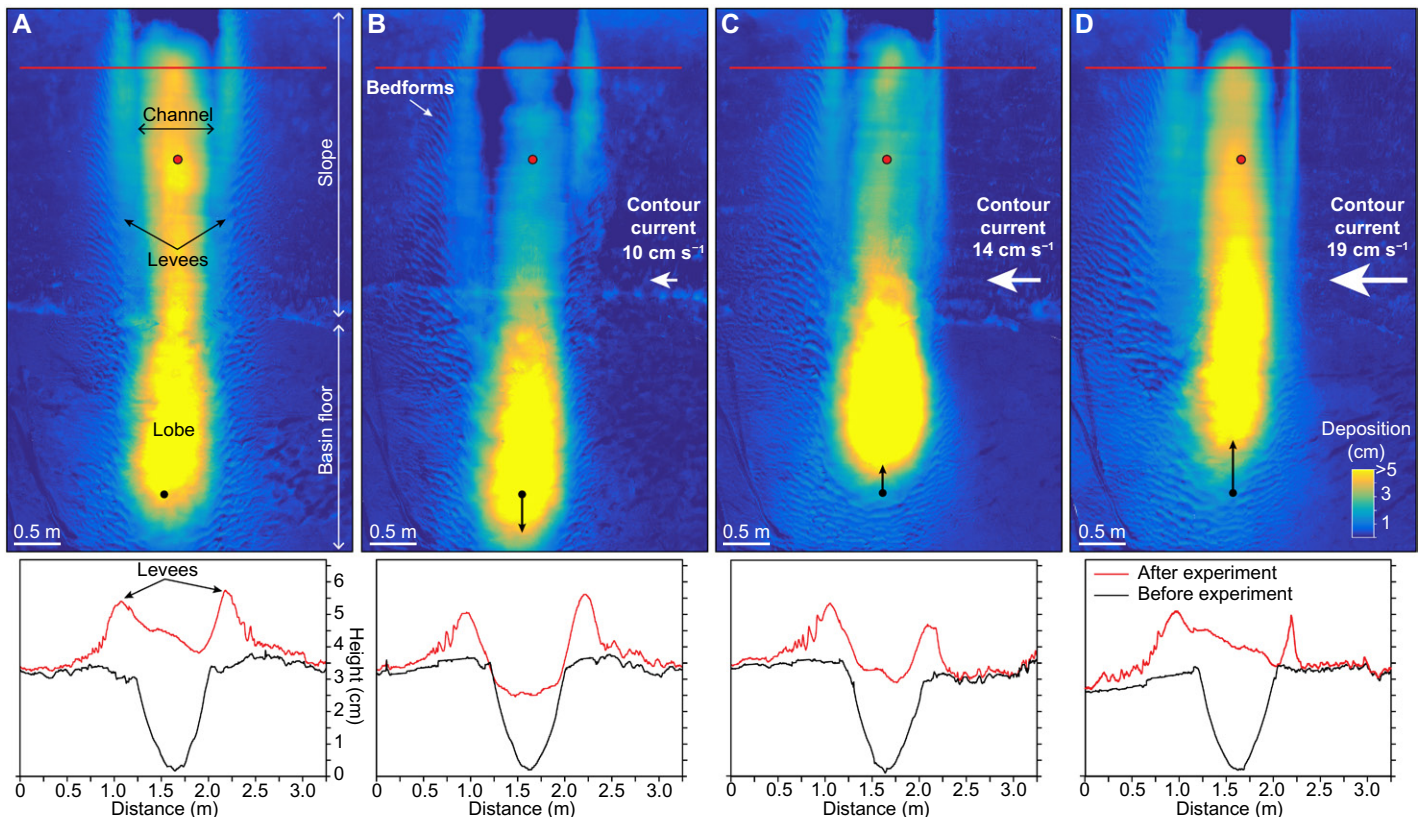
Figure 4. Deposition maps and cross sections during experiments of turbidity currents with no contour current interaction (A), and with interaction with contour currents of 10 cm s⁻¹ (B), 14 cm s⁻¹ (C), and 19 cm s⁻¹ (D). Red lines represent location of cross sections. Red dot represents the point of current velocity measurements. Black dots and black arrows represent how the frontal part of the deposit with sediment deposition >5 cm was displaced compared to the experiment in standing water. In the cross sections, black and red lines indicate the profile before and after the experiment, respectively.

Scotia, Canada (Campbell and Mosher, 2016), and not migrating downstream of the contour current as suggested for the South China Sea (He et al., 2013) and the Congo Basin, central Africa (Gong et al., 2018).

In our experiments, we observed flow instabilities at the lateral front that propagated along slope in the direction of the contour currents (Fig. 2B). Gong et al. (2018) suggested that Kelvin-Helmholtz billows and bores, formed in the pycnocline between turbidity and contour currents, could generate erosion on the channel flank located downstream of the contour current, and deposition upstream of the contour current. However, in our study, we observed the opposite pattern, and we conclude that billows and bores moving along slope on the top of the turbidity current did not play a crucial role in the generation of asymmetric channel-levee systems in these experiments. The asymmetry could be simply explained by the deviation of turbidity currents and by asymmetric overspill. The lateral front is important in blocking overspill and generating linear narrow levees when turbidity currents interact with strong contour currents (Fig. 4D), in agreement with the conceptual model suggested by Fonnesu et al. (2020) for the mixed turbidite-contourite system off northern Mozambique.

Combined Flows in Synchronous Mixed Systems

In our experiments, the velocity of most of the turbidity currents was higher than the velocity of the contour currents (Fig. 3A). The speed of the contour current and that of the turbidity current in standing water was equal at 9–11 cm above the flume floor (Fig. 3A), but the change in direction of the turbidity current was already observed 3 cm above the bed, where the turbidity-current velocity was >3× higher than the contour-current velocity (Fig. 3C). From this elevation upward, the direction of the velocity changed in a helical fashion until it was directed perpendicular to the downslope velocity at the base of the flow. Furthermore, the maximum downslope velocity within the channel as well as the travel distance of sediment onto the basin floor seemed affected by the contour-current strength (Figs. 3A and 4). But perhaps most importantly, the contour current greatly impacted the cross-sectional flow structure of the channelized turbidity current. This can be explained by the contour-current velocities of 10–19 cm s⁻¹ being an order of magnitude higher than the along-slope velocity components of the turbidity current in standing water (Fig. 3B). The resulting combined-flow structure displayed characteristics that belong to neither turbidity current nor contour current, but

a combination of both processes that represents a newly described marine environmental flow type. This combined-flow structure dominated the cross-sectional evolution of the channel-levee system. In conclusion, combined flow resulting from synchronous oceanic circulation and turbidity currents should be considered in the analysis of submarine channel systems on continental slopes, especially in zones of the slopes where turbidity currents are traveling down the slope at velocities of 2 m s⁻¹ or less, and where submarine channels are not deeply incised, favoring overspill and the interaction between turbidity currents and contour currents.

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