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Sediment waves control origins of submarine canyons

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We appreciate the interest of Gong et al. (2023) in our work, and thank them for their comments. This creates an opportunity to further develop the discussion about the interpretation of sediment waves, and the relationship between sediment waves and regularly spaced, along-slope migrating submarine canyons. Gong et al. (2023) concur that the regularly spaced canyons could be initiated by sediment waves, and that their subsequent development was mainly controlled by synchronous interaction between turbidity currents and bottom currents, which is not in contradiction to the main conclusion of Wang et al. (2023). Their comments allow us to clarify, which is helpful for understanding the origin and development of regularly spaced canyons. While agreeing that the seafloor morphology pre-13.8 Ma is consistent with the canyons/unidirectionally migrating deep-water channels being nucleated on sediment waves, Gong et al. question our interpretation of the morphology and seismic facies of the convex-up bodies that occur between them.

Wynn and Stow (2002) suggested that bottom-current sediment wave geometry varies laterally with flow conditions (of contour currents), and not that they are necessarily symmetrical. In fact, their quoted examples from the central Argentine Basin (Flood and Shor, 1988) and the Falkland Trough of the western South Atlantic Ocean (Cunningham and Barker, 1996) all show asymmetrical features.

Gong et al. note some features of the architecture of regularly spaced, convex-up seismic facies that they consider inconsistent with a sediment wave origin. During the development of sediment waves, regardless of origin, the downstream flank may experience lower deposition rates and even erosion when compared to the upstream flank (Flood, 1988). We readily acknowledge (and indeed explicitly state) that the overall geometry and internal architecture of these wave-like features is not wholly due to contour currents, highlighting that intermittent turbidity currents flow along wave troughs to erode canyons, which would further amplify the differences between the two flanks. It is perhaps purely a matter of semantics whether one defines sediment waves as those forms created solely by contour currents with no other influence.

We did not, in fact, specify the flow direction of the paleo-contour currents (cf. fig. 1 of Gong et al.), but pointed out that the directions of paleo-bottom currents were uncertain, and we cannot assume that the oceanographic regime obtained before 6.5 Ma, when the South China Sea was still open to the east, was similar to that of the present day. The relationship between migration direction and the direction of flow is therefore uncertain.

The lee wave model of Flood (1988) has been widely cited as a reasonable explanation for the formation of bottom-current sediment waves (e.g., Wynn and Stow, 2002). It can explain both the cross-sectional asymmetry of bottom-current sediment waves and their migration upstream (relative to bottom currents) (Flood, 1988). However, it cannot be denied that bottom-current sediment waves may also migrate downstream, and the theoretical possibility of downstream migration has also been demonstrated by Hopfauf et al. (2001). Our study highlighted the uncertainty of paleo-flow directions, and we do not define which is the upstream or downstream flank of the wave-like features.

As commented above, we have described the asymmetric features of the sediment waves and acknowledged that the model of Gong et al. (2018) is one possible process contributing to the downstream migration of the channels in the Lower Congo Basin, though as a general mechanism it cannot explain upstream migration of submarine channels (Miramontes et al., 2020), nor the regular spacing of canyons.

However, one should note that the interaction between turbidity currents and bottom currents includes two distinct situations: that of synchronous flows, and that of alternating interactions over a wide range of timescales (Mulder et al., 2006). The model of Gong et al. (2018) focused on synchronous interaction, though within a long-term geological history, it is probable to have both types of interactions. We do not refute the possible occurrence of synchronous interactions within canyons. However, there must be considerable theoretical uncertainty over the consequences of interaction between two roughly orthogonal currents, and the resulting bed-normal variation in curl of the mean flow vector. This is especially uncertain, given that neither velocity profiles nor, in the case of the turbidity current, density profiles are known, which means that the stability of the interface between the two currents cannot be defined. We prefer the model of Fuhrmann et al. (2020), supported by observations on the modern sea floor, offshore Mozambique, that shows wave asymmetry and contour/gravity current interactions comparable to those we propose.

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