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An integrated process-based model of tool marks in deep-marine systems: implications for flow prediction, the Bouma sequence, and hybrid event beds

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Tool marks are erosional sedimentary structures that are frequently observed on the base of beds in deep marine systems. However, their utility for interpreting rocks has largely been restricted to palaeocurrent information. In contrast, aggradational bedforms such as ripples, dunes, and antidunes have been extensively used for obtaining information concerning processes during deposition in addition to palaeocurrent information. In large part, the focus on palaeocurrent information from tool marks reflects our lack of understanding of their formative conditions. Whilst tool marks can occur in a variety of other environmental settings, including river floodplains, lacustrine systems, and shallow-marine systems, they are best known in deep-marine systems, and herein we restrict our analysis of them to such systems. Here we develop an integrated model of tool mark formation, by linking geological observations, predominantly recorded from the 1950s-1970s, to the advances in knowledge of flow dynamics since these observations were made. In particular, there have been key advances in the past 20 years in the understanding of transitional flow and debris flow dynamics. We show that some discontinuous tool marks (prod, bounce, skip and roll marks), and notably bounce (skim) marks, are associated with transitional flows that are able to support much of the weight of the tool through buoyant force. Similarly, some prod marks are associated with striations on their upstream flanks, again suggesting that flows were transitional and restricted particle rotation that normally occurs in particles with ballistic trajectories.

Continuous tool marks, notably grooves, have been associated with turbidity currents since the late 1950s, close to the birth of the turbidity current concept. Here we review the different arguments for the formative processes of grooves and demonstrate that they cannot be formed by turbidity currents, but are instead the product of debris flows that hold tools firmly within the flow, enabling regular, continuous grooves to be formed in cohesive substrates. Furthermore, these debris flows are typically components of flows that produce hybrid beds. This reinterpretation of groove formation overturns a paradigm that has held for almost six decades, and has major implications for the interpretation of deep-marine sediments. The Bouma sequence that we know today links the formation of grooves to turbidity currents. However, the formation of grooves by dominantly bypassing debritic flow components, and the successive development of grooves and then flutes as observed in some cases, demonstrate that the erosive surface and overlying deposits can be produced by very different types of current, and that there can be a time gap between the cutting of the basal erosive surface and the overlying deposits. Consequently, a grooved erosive surface is not a part of the sedimentological record of a waning turbidity current, and therefore the classical Bouma sequence. Additionally, the presence of grooves at the base of hybrid beds suggests that the simple longitudinal flow transformation model of hybrid beds from turbulent turbidity current at the front, through a following debris flow and then a dilute turbidity current (Haughton et al., 2009), is unlikely to be valid.