Turbidites, and the Case of the Missing Dunes (and sometimes ripples)

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Turbidites have long been recognized as being deposited from subaqueous turbidity currents (e.g. Kuenen and Migliorini, 1950). Turbidity currents are turbid mixtures of suspended sediment and fluid that move under the influence of gravity. Although not necessarily turbulent, most natural sand-transporting turbidity currents are, and it is the fluid turbulence that maintains sediment in suspension and hence sustains the needed density contrast between the flow and the surrounding ambient fluid. As turbidity currents begin to wane (decelerate), typically because of a reduction in slope, flow competence and capacity are reduced and sediment begins to deposit. Deposition, therefore, generally takes place under progressively less energetic flow conditions, which in turn should be manifest in the stratigraphic record as an upward-fining and upward-decreasing-energy (as recorded in the preserved physical sedimentary structures) succession. Such a succession was first documented by Bouma (1962) who recognized the now well-known 5-division succession commonly termed a classical, or Bouma turbidite (Fig. 1). At its base, the coarsest sediment commonly comprise a sharp-based, normally graded, structureless (i.e. no physical sedimentary structures) unit, termed the a-division, which then is sharply overlain by planar-laminated sandstone (b-division). These strata are succeeded upward by a small-scale cross-stratified unit (c-division) overlain by a diffusely parallel-laminated fine-grain unit (d-division) capped finally by a mud-dominated unit termed the e-division.
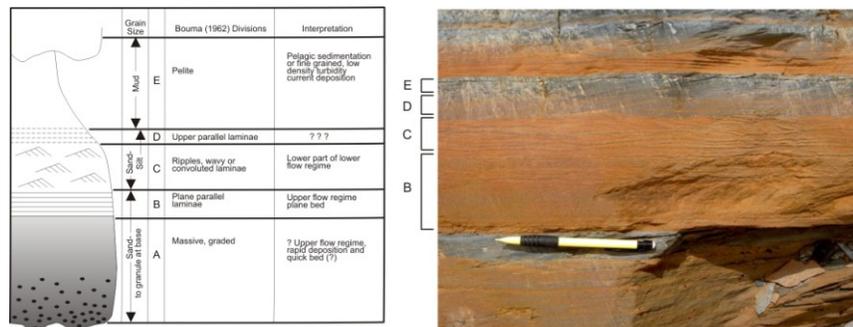

Fig. 1. Idealized model of a (Bouma) turbidite (schematic modified after Blatt et al., 1980) with an ancient example showing the position of the B through E turbidite divisions.

Of the five divisions, the first four are interpreted to be genetically related and sequentially deposited from a single decelerating turbidity current. The e-division, on the other hand, represents comparatively slow deposition from permanent hemipelagic and/ or pelagic sediment fallout. The a-division is generally attributed to deposition directly from suspension, whereas the b-, c-, and debatably the d-division, record bed-load transport and deposition. Parallel laminated sand or sandstone of the b-division is generally interpreted to indicate deposition under upper-stage plane bed conditions, whereas the small-scale cross-stratification of the c-division represents deposition from lower energy current ripples. However the almost ubiquitous superposition of current-ripple cross-stratification above planar-laminated strata in

classical turbidites has puzzled geologists for many years, because in a decelerating unidirectional flow, and in sediment coarser than about 0.15 mm (very fine sand), dune cross-stratification should occur between these two bed states. Even more perplexing is that in rare instances dune cross-stratification does occur where expected (Figs. 2A, B). The question, therefore, is why are conditions that form dunes typically suppressed or alternatively never developed in most decelerating turbidity currents?

Fig. 2. (A) thick-bedded turbidite consisting of planar-laminated sandstone (B-division) over lain by medium-scale (dune) cross-stratification (C1) overlain by small-scale (ripple) cross-stratification (C2). (B) sharp-based, medium-bedded turbidite in a levee succession composed of medium-scale (dune) cross-stratification (C1) overlain by small-scale (ripple) cross-stratification (C2). (C) thick-bedded turbidite consisting of a thick planar-laminated basal part (B-division) overlain gradationally by the diffusely planar-laminated D-division capped by the fine-grained E-division. Note the lack of an intervening C-division.

Paucity of Dunes in Turbidites

It is proposed that the rarity of medium-scale (dune) cross-stratification in most turbidites is because of the deleterious effect of suspended sediment. As a turbulent flow decelerates and bed-load transport begins, high sediment concentration causes flow separation downflow of any bed defects to be damped (e.g. Allen and Leeder, 1980). This, in turn, would prevent the initiation and amplification of ripples or dunes, and as a consequence bed-load sediment would continue to be moved as a few-grain-high bed forms forming upper-stage plane bed, presumably at flow speed below those that form plane bed in a clear-water unidirectional flow (compared Figs. 3A, B). Stated more specifically, the lower stability of upper-stage plane bed is depressed to lower flow speeds in concentrated flows compared to those in a clear-water flow (Fig. 3B). As conditions continue to wane, sediment concentration becomes sufficiently reduced so that dunes or ripples can form. In most currents, however, this condition develops when the flow is either moving too slowly or is composed of sediment too fine to form dunes, and as a consequence ripples succeed plane bed in the aggrading deposit. In the uncommon instance where dune cross-stratification follows upper plane bed, and then is capped by ripple cross-stratification, suggests that sediment concentration was sufficiently reduced, flow speed of appropriate order, and sediment sufficiently coarse that bed defects evolved into dunes, which with further deceleration were succeeded by current ripples (Fig. 3C).
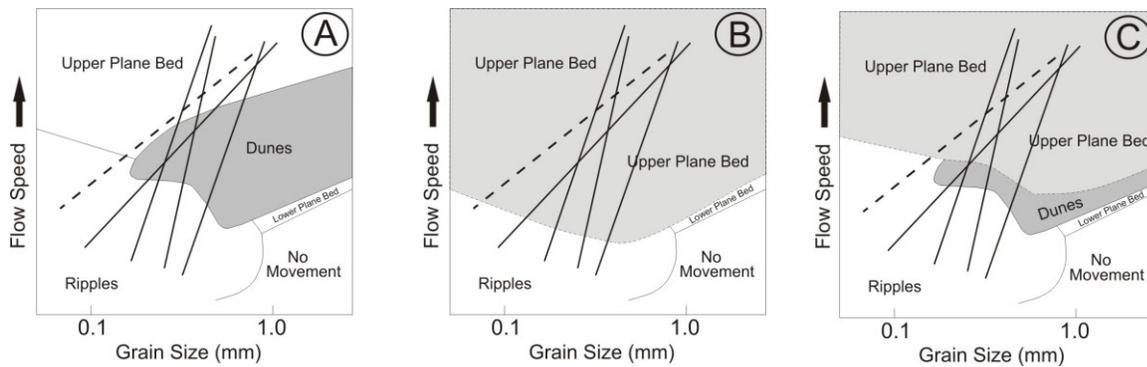
Fig. 3. (A) Stability diagram for unidirectional bed forms in a clear-water flow (modified after Southard and Boguchwal, 1990). Lines sloping down to the left trace out bed form changes in a hypothetical-decelerating flow. Note that except for the dashed line, all decelerating flows pass through the dune stability field before encountering the ripple field. (B) Hypothetical stability diagram for a high-concentration turbulent suspension. Throughout the deceleration history of the current, sediment concentration remains high and as a result the stability of upper plane bed is depressed downward into the dune and ripple stability fields. When sediment concentration becomes sufficiently reduced (due to flow waning) ripples most commonly develop because the flow is too slow or the sediment too fine to form dunes. (C) Hypothetical stability diagram for a turbulent suspension in which sediment concentration is reduced significantly during the event. Initially high-energy, high concentration conditions deposit upper plane bed. As flow speed and sediment concentration (and possibly also grain size) is reduced a point is eventually reached at which dunes become initiated and grow on the aggrading bed. As flow speed and/or grain size continue to decrease, dunes are replaced by ripples.

Another common observation in the rock record is turbidites composed of a lower b-division overlain by a d-division (Fig. 2C, 4). Importantly, there is no sharp grain size change across the transition, suggesting gradually changing flow conditions and related sediment deposition. The question, therefore, is the reason for the absence of an intervening c-division in a flow that apparently was experiencing gradual decelerating flow conditions, namely high-energy upper-stage plane-bed (b-division) succeeded by flow speed close to the bed-load threshold for sand (d-division).   Surely intermediate flow speeds that would have supported ripple development existed but somehow ripple development was suppressed. The most logical explanation, again, is the inhibiting influence of high-suspended sediment concentration that must have remained continuously high during the period of bed-load sand transport, and accordingly prevented the initiation and maintenance of ripples (Fig, 4).
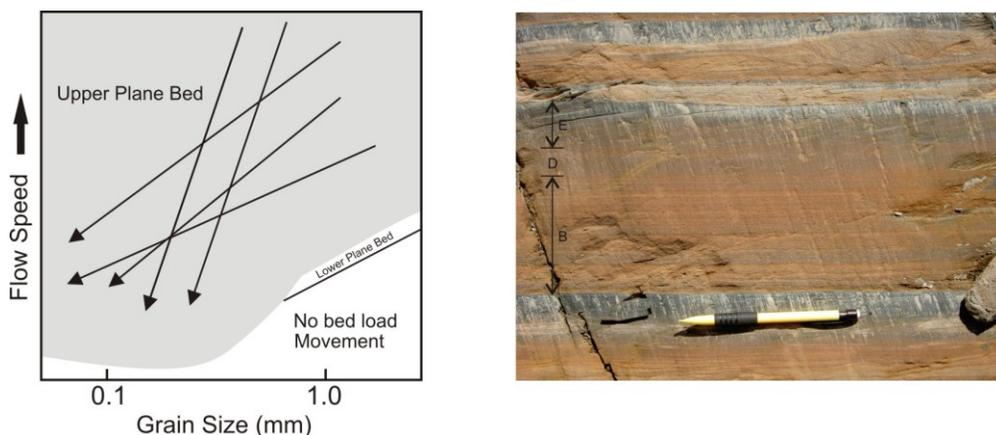

Fig. 4. Hypothetical stability diagram for a high-concentration turbulent suspension. Throughout the deceleration history of the current sediment concentration remains so high that upper plane bed remains stable until the cessation of bed load transport of even lower fine sand. In this case the planar-laminated b-division is succeeded upward by the subtly laminated d-divison.

Conclusions

The occurrence of the planar laminated b-division in some/many? turbidites may be more a consequence of sediment concentration than flow speed, and as such, its typical correlation with high speed, upper plane bed in clear-water unidirectional flows may grossly overestimate flow speed at the time of sediment deposition. In addition, the paucity of truly complete turbidites, in other words those containing a dune cross-stratified interval sandwiched between a planar laminated and ripple cross-stratified interval, suggests that the requisite combination of grain size, sediment concentration, and flow speed represent conditions that are rarely achieved in nature.

Acknowledgements

References

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