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Spaced High-Angle Cross-Stratified Sandstones Sets in Deep-Marine Strata of the Neoproterozoic Windermere Supergroup, Cariboo Mountains, British Columbia, Canada – Indicators of Cyclic Steps and Hydraulic Jump Unit Bar Sedimentation

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Although ubiquitous in fluvial strata, dune cross-stratified sandstone is comparatively rare in the deep-marine sedimentary record. In basin floor deposits of the Neoproterozoic Windermere turbidite system, graded, but generally poorly sorted, structureless coarse-grained sandstones (Bouma Ta division) are commonly, but locally, overlain by well-sorted, high-angle cross-stratified, coarse- to very coarse-grained sandstone that resembles dune cross-stratification. Moreover, these sandstones commonly have high intragranular porosity and a distinctive red colour related to a pervasive ferroan calcite cement with depleted (i.e. bacterially mediated) C13 values, both suggestive of early (near seabed) cementation. Cross-stratification typically occurs as a single set that generally is of the order of a few up to several decimeters thick – multiple (i.e. stacked) sets, however, are not uncommon. Set bases are erosional and oriented steeply downward into the underlying Ta part of the bed. In contrast, the top of the set remains more or less horizontal. This trough-shaped depression is then infilled with a single or multiple sets of individually normally graded, well-sorted cross-beds that collectively resemble ubiquitous dune cross-stratification in fluvial systems. Of note, however, is that high-angle cross-stratification commonly transitions upflow into planar-laminated sandstone. Viewed in the opposite direction, individual planar lamina pass continuously but abruptly downflow into a single cross-bed, which with aggradation of the upflow planar laminated unit forms a downward thickening (wedge-shaped) cross-stratified set. Further downflow, the cross-stratified unit thins rapidly and becomes replaced laterally by planar laminated sandstone, which in many cases terminates abruptly in an overturned fold ("swirl" structure). In addition, the planar- and cross-stratified unit is commonly capped by a single ripple cross-stratified set that similarly pinches out abruptly downflow.

Planar to high-angle cross-stratified sandstones form localized units separated by several Dm along the top of discrete Ta beds. The continuous ripple cross-stratified veneer that caps many of these units indicates that their localized development is not the result of post-depositional erosion. Alternatively it could be related to limited available sediment, however these structures overlie a sand-rich, areally extensive Ta bed substrate. Instead, the local development of these localized features is interpreted to be related to spaced hydraulic jumps, or cyclic steps. Specifically, the planar laminated part of the unit forms the upflow part of a hydraulic-jump unit bar that on its downflow side transitions sharply into a prograding depositional wedge forming well-sorted, “dune-like” cross-stratification.