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Quantitative characterisation of deltaic and subaqueous clinoforms

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Clinoforms are ubiquitous deltaic, shallow-marine and continental-margin depositional morphologies, occurring over a range of spatial scales (1–104 m in height). Up to four types of progressively larger-scale clinoforms may prograde synchronously along shoreline-to-abyssal plain transects, albeit at very different rates. Paired subaerial and subaqueous delta clinoforms (or 'delta-scale compound clinoforms'), in particular, constitute a hitherto overlooked depositional model for ancient shallow-marine sandbodies. The topset-to-foreset rollovers of subaqueous deltas are developed at up to 60 m water depths, such that ancient delta-scale clinoforms should not be assumed to record the position of ancient shorelines, even if they are sandstone-rich.

This study analyses a large dataset of modern and ancient delta-scale, shelf-prism- and continental-margin-scale clinoforms, in order to characterise diagnostic features of different clinoform systems, and particularly of delta-scale subaqueous clinoforms. Such diagnostic criteria allow different clinoform types and their dominant grain-size characteristics to be interpreted in seismic reflection and/or sedimentological data, and prove that all clinoforms are subject to similar physical laws.

The examined dataset demonstrates that progressively larger scale clinoforms are deposited in increasingly deeper waters, over progressively larger time spans. Consequently, depositional flux, sedimentation and progradation rates of continental-margin clinoforms are up to 4–6 orders of magnitude lower than those of deltas. For all clinoform types, due to strong statistical correlations between these parameters, it is now possible to calculate clinoform paleobathymetries once clinoform heights, age spans or progradation rates have been constrained.

Muddy and sandy delta-scale subaqueous clinoforms show many different features, but all share four characteristics.

(1) They are formed during relative sea-level stillstands (e.g., Late Holocene); (2) their stratigraphic architecture and facies character are dominated by basinal processes, and are quite uniform; (3) their plan-view morphology is shore-parallel and laterally extensive; (4) their sigmoidal cross-sectional geometry contrasts with the oblique profiles of most subaerial deltas. Holocene-age, delta-scale, sand-prone subaqueous clinoforms occur on steep ($\geq$0.26°) and narrow (5–32 km) shelves, at typical distances of 0.6–7.2 km from the shoreline break. That contrasts with mud-prone subaqueous deltas, which form clinoforms on gently-sloping (0.01–0.38°), wide (23–376 km) shelves, at usual distances of 7.5–125 km from the shoreline. Delta-scale sand-prone subaqueous clinoforms have diagnostically steep foresets (0.7–23°). Similarly steep gradients were observed in much larger shelf-prism- and continental-margin-scale clinoforms. Gentler foreset gradients are shown by sand-prone subaerial deltas (0.1–2.7°), and mud-prone subaqueous and subaerial deltas (0.03–1.50°). Due to the lack of connections with river mouths, Holocene delta-scale sand-prone subaqueous clinoform deposits have progradation rates (1–5 $\times$ 10(2) km/Myr) and unit-width depositional flux (1–15 km2/Myr) that are up to 3–4 and 2–3 orders of magnitude lower, respectively, than age-equivalent input-dominated subaerial deltas and muddy subaqueous deltas. Lower progradation/aggradation ratios are reflected in a larger spread of clinoform trajectory angles (from$-$0.4° to+3.5°) than the very low values displayed by age-equivalent subaerial and muddy subaqueous deltas.

As slowly prograding, steep, sigmoidal clinoforms are strongly suggestive of sand-prone subaqueous deltas, the Sognefjord Formation and Bridport Sand are likely Jurassic examples of this clinoformtype, and host hydrocarbon reservoirs. In contrast, the Campanian Blackhawk Formation is an outcrop example of delta-scale compound clinoforms with a muddy subaqueous component.