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ORIGINAL RESEARCH ARTICLE

Mixed depositional processes in coastal to shelf environments: Towards acknowledging their complexity

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1 | WHAT ARE MIXED-ENERGY DEPOSITIONAL PROCESSES?

Mixed-energy depositional processes refer to the interplay of hydrodynamic processes controlling sedimentation dynamics in a certain sedimentary environment. When referring to the coastal to shelf realm, three main suites of processes are considered the major players: river, tide and wave (Ainsworth et al., 2011; Dalrymple et al., 1992; Dashtgard et al., 2021; Zuchuat et al., 2019). In addition to the cyclical or punctual intrinsic variations in these processes, aeolian processes, contour currents, seasonal ice cover, nature and mechanical characteristics of the substrate and confinement and physiography of the basin, climate oscillation (e.g. El Niño and La Niña) and relative sea-level fluctuations can interact with or affect the three major processes and should also be considered in sedimentary analyses. In modern settings, the qualification of depositional processes relies on direct measurements

(e.g. current velocities, water-level changes, wave heights, suspended sediment concentration, clay concentration). Quantitative measurement can then be integrated with more qualitative descriptions of the resulting sedimentary products (i.e. morphologies, bedforms) and biogenic elements (i.e. trace fossils) (Dashtgard et al., 2009; Vaucher et al., 2018; Vaucher & Dashtgard, 2022; Yang et al., 2008; Yang & Chang, 2017). In addition, experimental studies have helped refine the interpretation of individual and combined processes from bedforms, which, although not diagnostic of a specific depositional environment, can be used to reconstruct sedimentary processes and, therefore, aid palaeoenvironmental interpretations (Arnott & Southard, 1990; Baas et al., 2021; Cummings et al., 2009; Dumas et al., 2005; Dumas & Arnott, 2006; Myrow et al., 2018; Perillo et al., 2014; Sato et al., 2011; Southard et al., 1990; Southard & Boguchwal, 1990).

Stratigraphic models and facies interpretations were historically developed for the major end-member processes

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(i.e. river, wave, tide) and compared to modern systems in order to propose relatively simple and predictable sedimentary architectures applicable to ancient sedimentary successions (Ahmed et al., 2014; Clifton, 2006). This approach aimed to fit ancient sedimentary successions into these end-member schemes and the relative simplicity of these models has been useful in applied contexts, such as hydrocarbon exploitation. However, although most modern coastal to shelf environments are dominated by one of the three main processes, additional 'secondary' processes almost always operate and impact sedimentary dynamics. In turn, the term 'mixed depositional processes' is more frequently used to encompass the various hydrodynamic process at play and identified in the ancient sedimentary systems (Collins et al., 2017; Dashtgard et al., 2021; Gugliotta, Flint, et al., 2016a; Gugliotta, Kurcinka, et al., 2016b; Rossi & Steel, 2016; Vakarelov et al., 2012; Vaucher et al., 2017). In the literature, most workers use qualitative nomenclature to describe or define an environment in terms of processes, for example *tidally modulated shoreface*, or *wave-dominated delta*. The terms affected, influenced and modulated are often used to suggest that the secondary process is of relatively low, medium and high energy, respectively (Dashtgard et al., 2012, 2021).

The interplay of different processes in coastal-shelf systems can be cryptic to decipher, especially in the rock record. This is because the preserved sediments may only reflect the dominant processes active at the time of deposition, rather than background processes active over longer timescales (Collins et al., 2018; Van Yperen et al., 2020). Infrequent extreme events can also offset and erase decadal and potentially longer timescale trends from the sedimentary record (Harley et al., 2022). Furthermore, modern data seem to indicate that there is no linear correlation between the intensity of extreme events and the amount of sediment being eroded or deposited near coastal systems, which further complicates the interpretation of the preserved signals (Guisado-Pintado & Jackson, 2019). Finally, the amount of progradation-erosion along coastlines is extremely heterogeneous, which will impact the preserved sedimentary architecture (Zuchuat et al., 2023), despite documented long-term regressive or transgressive trends. Uncertainties in interpreting the exact nature of the hydrodynamics that generated specific sedimentary structures always remain when analysing the sedimentary record. Indeed, different hydrodynamic conditions can result in identical sedimentary signatures and one specific set of hydrodynamics can generate different bedforms ('non uniqueness' sensu Burgess & Prince, 2015). Furthermore, certain systems are or were dominated by a single depositional process, yet their deposits lack any characteristics commonly assigned to such systems: for example, the Venice lagoon is tide-dominated, yet no

tidal rhythmites are preserved in the sediments (Ghinassi et al., 2018). However, despite these challenges and the impact of many other processes beyond river, wave and tide, several studies have used a proposed workflow based on historical process interpretations of sedimentary structures to quantify the influence of only these three processes on sedimentary successions and assign an environmental classification (Peng et al., 2018; Rossi et al., 2017).

The appraisal of mixed-process coastal to shelf depositional environments has moved forward significantly during the past two decades. Notably, a multitude of new depositional models for various types of mixed-energy environments and sub-environments now exist that: (1) have recognised relationships and patterns between sedimentary structures, facies, stratigraphic architecture and processes across numerous scales of stratigraphic observations; and (2) have been jointly developed for modern and ancient sedimentary systems, or at least calibrated from ancient to modern systems (or vice versa; Collins et al., 2017, 2020; Dashtgard et al., 2009, 2012, 2021; Gugliotta, Flint, et al., 2016a; Gugliotta et al., 2015; Pemberton et al., 2012; Vakarelov et al., 2012; Vaucher et al., 2017, 2018; Yang et al., 2005, 2006, 2008). The cumulative step forward offers a holistic, observation-driven toolset for palaeoenvironmental reconstructions for geoscientists, beyond simply focussing on the entrenched interpretation of the relationship between sedimentary structures and wave/river/tide processes. However, while these recent advances were significant, major aspects remain unclear, especially how mixed-process environments evolve in response to changing climate, sea level, sediment supply, accommodation, or basin physiography, among other factors (Zuchuat et al., 2022). These external factors are difficult to capture because they can occur away from the studied localities and because depositional models are often static.

After several technical sessions ran on this topic during past International Meetings of Sedimentology (Rome in 2019, Prague in 2021), the European Geosciences Union General Assembly (Vienna in 2020) and the International Sedimentological Congress (Beijing in 2022), we took the initiative of organising this special issue to gather and bring new data from experiments, numerical modelling and fieldwork, that define and refine the way sedimentologists and geoscientists in general, comprehend mixed-energy coastal to shelf environments.

2 | WHAT IS NEW IN MIXED-ENERGY DEPOSITIONAL PROCESSES?

This special issue includes seven contributions that show some of the key factors controlling the sedimentary

dynamics of coastal to shelf environments (Figure 1). This is a brief summary of all of them.

Pierik et al. (2023) show how resistant layers can play a major role in controlling the dimension and position of estuarine channels and bars which, in turn, affect depositional and erosional processes and their interactions in these environments. In the Ems–Dollard estuary (The Netherlands), resistant layers (e.g. bedrock, consolidated peat, or stiff pre-Holocene clays and tills) can limit channel depth resulting in increased channel curvature and width and lead to the formation of a mid-channel bar. The authors show that these effects can be expected in other similar estuarine and deltaic systems worldwide, highlighting that resistant layer effects are essential to consider as part of mixed depositional processes in coastal environments, especially under current and projected sea-level rise.

Valencia et al. (2023) use numerical simulations to explore the influence of syn-sedimentary compaction on delta morphodynamics. The approach relies on a novel inclusion of simplified compaction algorithms within the Delft3D modelling package and subsequent morphometric analysis. The authors show that higher compaction rates result in increased accommodation which, in turn, causes lower rates of delta top area increase, more evenly distributed sediment across the delta and more sediment retention in the delta top compared to the delta front and prodelta. This study shows it is crucial to understand the impact of syn-sedimentary compaction on deltas, a largely unexplored relationship due to difficulties with collecting accurate field data and the previous lack of compaction algorithms in high-fidelity modelling packages (such as

Delft3D). Understanding these relationships is essential to accurately predict coastal response to a changing global environment, for example the impact of sea-level rise on delta compaction. These questions are also necessary for better forecasting of deltaic responses to environmental variables and to increase our ability to characterise and model subsurface reservoirs and aquifers.

Wroblewski and Morris (2023) focus on the Upper Jurassic Red Shale Member of the Sundance Formation and the overlying Windy Hill Member of the Morrison Formation (USA). The authors illustrate how a careful sedimentological and ichnological study of outcrops can: (i) recognise the transition between storm-dominated to tide-dominated depositional processes in sedimentary basins, which, in turn, can (ii) confirm (or disprove) geochemistry-based basin-circulation hypothesis; and (iii) help understand the genesis of regional, composite stratigraphic surfaces. The robust ichnological and sedimentological analyses of these two stratigraphic units support the interpretation of a key stratigraphic surface as reflecting both forced regressions and normal progradations occurring simultaneously in different places at different times, with major implications on the timing and volume of reworked sediments in the basin.

Nugraha et al. (2023) combine extensive outcrop-based sedimentology with stratigraphic and palaeogeographical analysis to establish an improved depositional model and stratigraphic evolution of Neogene successions in the Kendari Basin, South-East Sulawesi, Indonesia. The stratigraphic relationships and onshore-to-offshore relationships of four formations are described and discussed and a wide variety of depositional facies and units are

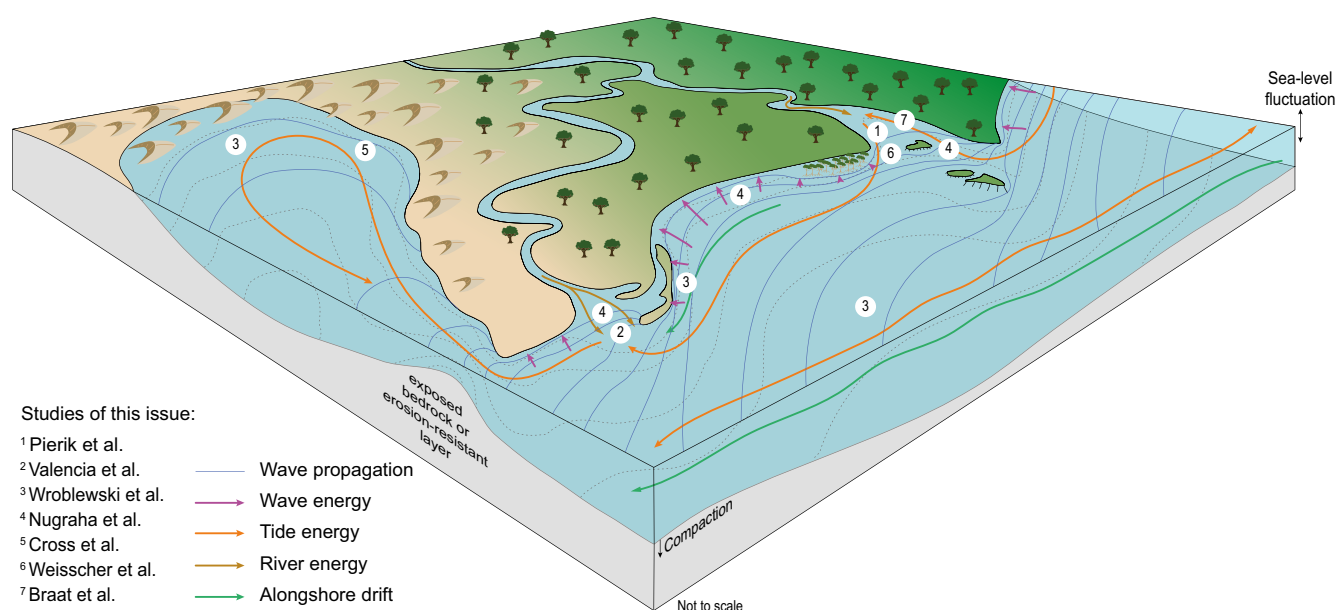


FIGURE 1 Sketch diagram illustrating the various hydrodynamic processes occurring in coastal to shelf environments, with numbers referring to articles from this issue.

recognised. Clastic environments include braided river channels, fluvial-tidal channels, tidal flats, mouth bar complexes and shoreface deposits. Shallow-marine carbonates and transgressive, landwards-backstepping carbonate platform architectures are also described and interpreted. An important Miocene–Pliocene unconformity is interpreted to relate to uplift across the coastal plain and hinterland, resulting in base-level fall below the shelf edge, recognised by conglomeratic fluvial channel infills in proximal areas and forced regressive shoreline deposits in more distal areas. The subsequent phase of base-level rise is associated with transgressive lags, backstepping reefal carbonates, more tidally influenced clastic shoreline deposits and reduction of the channel/overbank ratio in delta plain strata. Overall, these outcrop-based insights provide the foundation for an onshore-to-offshore stratigraphic model extending into the unexplored frontier basin surrounding South-East Sulawesi.

Cross et al. (2023) investigate the Jurassic aeolian-marine Curtis-Summerville sedimentary successions of central Utah (USA) and focussed on the nature of the aeolian stratigraphic record. The authors assessed relationships between aeolian and marine sub-environments, which were influenced by repeated transgression (T) and regression (R) periods. They develop a novel sequence stratigraphic model for aeolian-marine systems combining photogrammetry and sedimentary analysis. This work suggests that the deposition and preservation of an aeolian-marine marginal succession is controlled by both the transgressive or regressive nature of the system and by the scale of the tidal influence. During normal regression, marine sediments are influenced by processes such as waves and tides while aeolian dune fields expand; during transgression, the aeolian system deflates. This is an intuitive relationship; however, if regressions are rapid and of high magnitude, this can also result in the retraction of the erg and sediment starvation in contemporaneous shallow-marine deposits. This complex interaction is modified by the particular physiography of the Curtis Sea Basin, which results in amplified tidal forces. The increased tidal influence can make the identification of sequence stratigraphic boundaries challenging. However, the authors overcome this limitation by attributing deflationary surfaces to major changes in relative sea level, with consequent changes in depositional environments at T-R sequence scale.

Weisscher et al. (2023) use scaled laboratory experiments to study the morphological and hydrodynamic development of filling estuaries during sea-level rise. The objective was to study how estuarine systems could adapt to sea-level rise and whether the land-level rise is likely to keep up with the sea-level rise in these environments. Their experiments looked at the deposition of sand and mud and their interaction with vegetation in a tilting flume,

simulating the bi-directional tidal currents in estuaries. They present a mechanism through which natural systems could drown during the sea-level rise, even when enough sediment is available to fill the accommodation space. This is mainly observed furthest away from marine and fluvial sediment sources. Sediment is retained in the bay-head delta and close to the tidal inlet. The tidal embayment in between these locations drowned. This reduced vegetation survival and sprouting potential, as prolonged inundation increased mortality, negating the potential eco-engineering effect.

Braat et al. (2023) studied the relationship between the surface (horizontal) and subsurface (vertical) expression of mud in tidal bars and its morphodynamic and stratigraphic implications. Due to the limited availability of field data on the lateral and vertical depositional record of mud, new field data was gathered from the Shoal of Walsoorden (Western Scheldt estuary, the Netherlands) and analysed for this study. This was complemented with numerical modelling to better understand where mud accumulates. Results show that mud accumulation increases shoal elevation, which reduces flow over the shoal and, therefore, chute channel formation. This stabilises bar morphology and further promotes mud deposition and vegetation settling. Mud is therefore shown to play an important role in the development of estuarine morphology, but this effect may not be identified in the depositional record as only a small fraction of mud is preserved in the stratigraphy. Although mud cover at the surface was found to be relatively high (20%–40% of the intertidal area), mud constitutes only a small percentage of the total estuary volume (*ca* 5%), showing a mismatch between surface and subsurface expression of mud.

3 | WHAT IS NEXT IN MIXED-ENERGY DEPOSITIONAL PROCESSES?

For decades, geoscientists have tried to decipher the dynamics and controls of coastal to shelf depositional environments and summarise them in static facies and environmental models. Although these models have allowed comparisons between systems and advancement of the topic, there is still a need to develop new models that capture more fully the complexity and dynamic nature of mixed-energy coastal to shelf systems, notably by incorporating well-known oceanographical concepts and fluid mechanics into coastal to shelf depositional models. These depositional environments quite possibly show a higher inter-system variability, more complex intra-system dynamics and a higher susceptibility to external changes than other depositional environments. Consequently, studies of

coastal to shelf environments require wide integrated approaches, perhaps more so than any other sedimentary environment: facies, stratigraphy, ichnology, palaeontology, geochemistry, numerical modelling, physical experiments, modern analogue studies and other approaches all provide unique insights for characterising coast to shelf erosion, transport and sedimentation. This special issue intends to showcase the breadth of ongoing research and strives to take our understanding of the complexity of these depositional environments a step further. Understanding this complexity is intensely relevant and a major challenge for future sedimentary research, with implications for climate change, coastal management, carbon cycling, coastal aquifers and the energy transition.

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DATA AVAILABILITY STATEMENT

This intro paper has no data attached to it, but all the submissions compiled in this special issue have. Please refer to the respective author's publication for details on their datasets.

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The * symbol highlights the contributions to the Special Issue.

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