SEDIMENTOLOGY the journal of the International Association of Sedimentologists

Sedimentology (2021) **68**, 1289–1296 doi: 10.1111/sed.12881

Supercritical-flow processes and depositional products: Introduction to thematic issue

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Recent advances in clastic and carbonate sedimentology have seen a resurgence of interest in the dynamics of bedform development under supercritical flow conditions, that is under unidirectional currents at Froude numbers (*Fr*) values higher than unity. Concomitantly, increasing steps have been taken to better constrain the recognition criteria (at bed and architectural scales) and preservation potential of sedimentary facies in corresponding deposits. Knowledge of subcritical-flow bedforms (namely, ripples and dunes) and resulting facies has a long history, initially inspired by experimental work (Gilbert, 1914; Nevin, 1946; Bagnold, 1947; McKee, 1957a; Simons & Richardson, 1961; Allen, 1965; Simons *et al.*, 1965) followed by observations in numerous environmental settings (e.g. Kindle, 1917; Hülsemann, 1955; Sundborg, 1956; Fahnestock, 1963; Harms & Fahnestock, 1965; Coleman, 1969). These were validated successively by countless analyses of stratal successions from different ages and depositional environments in which a variety of styles of cross-lamination and cross-bedding frequently represented dominant facies signatures (e.g. McKee, 1939, 1957b; McKee & Weir, 1954; Oomkens & Terwindt, 1960; Allen, 1963, 1973; Coleman & Gagliano, 1965; Jopling, 1967; Harms, 1979; Ashley, 1990) relatable to lower-flow-regime processes. Conversely, research on upper-flow-regime processes has long been restrained by the ingrained persuasions that: (i) formative flows would take place under rare, high-energy events; and (ii) the preservation of resulting deposits in the stratigraphic records would be highly unlikely due to post-depositional reworking by waning-flow stages or long intervening times between episodes of significant accumulation. A notable exception was represented by the nearly ubiquitous recognition of planar-laminated facies attributed to upper-flow-stage plane beds, although strictly speaking these are formed under transcritical flow conditions (Stokes, 1947; Walker, 1965; McKee *et al.*, 1967; Williams, 1971). As a consequence, sedimentary facies related to supercritical-flow conditions have traditionally been considered of secondary relevance in clastic facies analysis, and have been only cursorily dealt with in sedimentology courses and textbooks. Possible exceptions to these tenets had long been recognized in successions from depositional systems more frequently affected by high-discharge, statistically 'catastrophic' hydrological events, such as alluvial fans, subglacial and proglacial settings, dryland rivers and volcaniclastic environments, wherein the occurrence of supercritical-flow signatures has been more commonly acknowledged (Power, 1961; Rahn, 1967; McDonald & Banerjee, 1971; Williams, 1971; Schmincke *et al.*, 1973; Gustavson, 1974; Stear, 1985; Blair, 1987; Langford & Bracken, 1987; Brennand, 1994).

Research over the last few years has clearly shown that sediment transport and deposition in the supercritical flow regime is much more abundant in stratal records from a broad range of depositional environments, from fluvial and lacustrine (e.g. Fielding, 2006; Allen *et al.*, 2014; Fricke *et al.*, 2015; Normandeau *et al.*, 2016; Gall *et al.*, 2017; Wang & Plink-Björklund, 2020) to coastal and shallow-marine (Ventra *et al.*, 2015; Hughes Clarke, 2016; Kostic *et al.*, 2019; Slootman *et al.*, 2019; Di Celma *et al.*, 2020), to

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more distal marine settings where sediments are dominantly transported by turbidity currents (e.g. Postma *et al.*, 2009; Covault *et al.*, 2014; Symons *et al.*, 2016; Lang *et al.*, 2017; Shao *et al.*, 2021). For a long time, antidunes and corresponding sedimentary structures captured the most attention in supercritical sedimentology, owing to their (as yet partly unresolved) morphodynamic complexities, their potential for palaeohydraulic estimates, and their occurrence in successions originating from both continental and marine environments (e.g. Hand, 1974; Shaw & Kellerhals, 1977; Schumm *et al.*, 1982; Barwis & Hayes, 1985; Alexander & Fielding, 1997; Carling & Shvidchenko, 2002; Yokokawa *et al.*, 2010; Froude *et al.*, 2017). However, a significant stimulus to the resurgence of interest in supercritical-flow phenomena has come through the gradual recognition of a new bedform category – cyclic steps – which were originally recognized mainly from observations in hydraulic engineering works and laboratory or numerical experiments (Mastbergen & Bezuijen, 1988; Winterwerp *et al.*, 1992; Parker, 1996; Parker & Izumi, 2000; Kostic & Parker, 2003; Spinewine *et al.*, 2009), and whose occurrence in active depositional settings went long unrecognized due to the large scale and relative inaccessibility of the studied subaqueous systems, where they were long described as generic 'sediment waves' (e.g. Trincardi & Normark, 1988; Migeon *et al.*, 2000; Lee *et al.*, 2002; Normark *et al.*, 2002). The recent identification of cyclic steps as a new category of stable bedforms formed at elevated values of Froude number (Yokokawa *et al.*, 2009; Kostic *et al.*, 2010; Kostic, 2011; Cartigny *et al.*, 2014) has caused a marked shift of research focus on flow supercriticality in subaqueous (mostly submarine) density currents (e.g. Fildani *et al.*, 2006, 2013; Lamb *et al.*, 2008; Postma *et al.*, 2014; Zhong *et al.*, 2015; Lang *et al.*, 2017; Li & Gong, 2018; Cornard & Pickering, 2019; West *et al.*, 2019); however, it has also spurred a general reprisal of interest in upper-flow-regime processes. For example, a growing number of papers are demonstrating that supercritical-flow sedimentary structures are abundant, if not even dominant, in certain kinds of alluvial successions (Fielding, 2006; Fielding *et al.*, 2011; Plink-Björklund, 2015), in which they provide important palaeohydrological and palaeoclimatic information (e.g. Allen *et al.*, 2011, 2014; Gall *et al.*, 2017; Wang & Plink-Björklund, 2020), and are informing possible new approaches to a genetic categorization of ancient fluvial channel fills more strictly tied to the hydrology and (palaeo)discharge regimes of formative channels, rather than planform patterns (Fielding *et al.*, 2018).

A factor that still undermined progress in the general understanding of upper-regime bedforms is that their morphodynamics evolve through complex patterns of spatially and temporally variable processes, leading to repeated phases of bedform generation and dissipation governed by feedbacks between the continuously changing bed topography and the flow field. Compared to much better known dynamics of flow-bedform interactions under subcritical conditions, the supercritical stage is characterized by inherent instabilities and by stochastic to quasi-cyclic changes in bedform processes that only recently have been characterized from observational evidence. Nonetheless, the technical challenges involved in reproducing such phenomena in laboratory flume experiments imply that such observational evidence under controlled conditions is still relatively scarce (although rapidly growing; Alexander *et al.*, 2001; Yokokawa *et al.*, 2009, 2010; Cartigny *et al.*, 2014; Fedele *et al.*, 2016) compared to the knowledge base accumulated on ripple and dune bedforms. Scaling issues, given the frequently large size of bedforms documented in natural environments, remain to be addressed. The theoretical foundations to grasp the role of supercritical-flow processes have been classically discussed in-depth in literature on fluid mechanics and hydraulic engineering (Kennedy, 1963; Reynolds, 1965; Parker, 1996; Núñez-González & Martín-Vide, 2011), but not from a perspective informing process sedimentologists on how to link hydraulic phenomena to the nature of the depositional record. In summary, the outstanding complexity of supercritical-flow processes remains only superficially known to a vast majority of sedimentary geologists. Progress in this field is needed to enhance our ability to recognize and characterize upper-regime bedforms and corresponding sedimentary structures, to extract process and palaeoenvironmental information, but also to curb the uncritical attribution of stratal signatures to supercritical-flow processes where evidence may be insufficient or ambiguous, a problem particularly felt in the analysis of ancient stratigraphic records.

This special issue of *Sedimentology* was preceded by a pre-conference workshop held on the occasion of the 20th International Sedimentological Congress at Quebec City (Canada) in August

2018, titled 'Supercritical-Flow Processes and Bedforms: State of the Art and Future Directions'. The meeting brought together numerous workers active in various disciplines within sedimentary geology and approaching the analysis of sedimentary successions and (palaeo)flow reconstructions from various perspectives, from experimental analogue modelling to outcrop studies. The successful attendance of the workshop and the ensuing, long-lasting discussions among colleagues have inspired the compilation of this thematic issue, which to the editors' knowledge represents the first published collection of articles discussing different aspects of supercritical-flow sedimentology from multidisciplinary perspectives. While by no means intending to provide an exhaustive overview of the problematics, and especially of the debates, in this rapidly evolving field of sedimentary geology, this issue aims to offer readers a broad overview of some of its recent developments, as well as examples of the varied investigative approaches that sedimentologists and geomorphologists are following to tackle the remaining research questions. In view of this, the articles in this collection are presented according to the main research methodology: first those discussing results of experimental modelling, followed by data analyses from currently or recently active systems, concluding with analyses of stratigraphic records.

While the majority of flume studies on supercritical-flow phenomena have simulated transport of sand-dominated sediment under open-channel flows, more evidence is needed to verify the nature of processes involving more heterogeneous textural mixtures and more complex flow configurations. Two such examples are comprised in this article collection. Lang *et al.* (2021) document datasets from analogue experiments conducted in a tank on three-dimensional jets expanding from an outlet into ambient water bodies, modelling deposition in environments typically characterized by high-energy expanding flows, such as subaqueous proglacial ice-contact fans and channel-lobe transition zones of deep-water turbidite systems. At the flow outlet, momentum-dominated erosive jets form radial scours rimmed by an asymmetrical mouth-bar, established where density flows expand and become depositional. The proximal mouth-bar is characterized by trains of large antidunes indicative of dominant deposition under supercritical conditions, transitional to smaller, asymmetrical bedforms in the distal sector. The role of several parameters (for example, initial differential density, depositional gradient, dominant grain size and sediment supply) is systematically investigated to provide additional insights into the process–product variability encountered in actual depositional environments. Ono *et al.* (2021) present flume experiments aimed at documenting the morphodynamics of cyclic steps on sediment beds comprising a broad textural range, reflecting more accurately natural phenomena that mobilize clastic debris from clay to gravel. Their work demonstrates that, in the presence of clay, cohesion can be an additional factor governing the development of bedforms and especially partial preservation in the depositional record, and that the segregation of different textural classes within deposits partly reflects the nature of hydraulic-jump phenomena and longitudinal flow transitions inherent to the dynamics of active cyclic steps.

Studies of recently active systems also provide invaluable insights to the interpretation of ancient stratal records. Fildani *et al.* (2021) present a case study from the La Jolla submarine canyon-channel system offshore southern California, integrating high-resolution seafloor topographic surveys, seismic reflection data, sediment cores and hydrodynamic flow modelling. The authors show that scour trains consisting of erosional cyclic steps formed by turbidity currents that spill out of the La Jolla channel are important in the incipient formation of an adjacent channel, shedding light on the role played by supercritical flows in the large-scale organization of turbidite systems. Distally in the system, upstream of the terminus of the La Jolla channel, thin non-stratified supercritical turbidity currents overflow the relatively low-relief confinement of the channel. These levée–overbank currents produce cyclic steps an order of magnitude shorter (80 to 500 m) here compared to those observed on other submarine fans (0.5 to 10 km). Chen *et al.* (2021) investigated the relationship between supercritical flows and submarine channel morphology at system scale, providing insights into the dynamics of knickpoints and superimposed crescentic bedforms along the subaqueous delta slope of Bute Inlet (British Columbia, Canada). The floor of the 44 km long submarine channel is characterized by a series of knickpoints spaced at distances of hundreds to thousands of metres, with smaller superimposed bedforms varying in wavelength from a few tens of metres proximally to over

100 m distally. Direct flow-field measurements reveal the evolution of flow parameters while passing over knickpoints. On the basis of sediment cores extracted along a single knickpoint, the authors propose a preliminary model for the relationships between flow dynamics, preservation potential and the spatial distribution of facies associated with knickpoints and associated bedforms. Besides deep-water turbidite systems and deltas, the margins of insular or peninsular volcanic massifs represent probably the third most frequently recognized setting for the occurrence of cyclic steps in modern subaqueous settings. Casalbore *et al.* (2021) compile an overview of the morphometrics, spatial distribution, formative mechanism and reconstructed morphodynamics of cyclic-step bedforms identified along submarine volcanic flanks at various localities worldwide. They recognize that distinct bedform scales (tens to hundreds of metres versus hundreds to thousands of metres in wavelength) and genetic categories (origin by density currents or by subaqueous slope instability) are partly related to geomorphic attributes and bathymetric profiles of the hosting volcanic apparati, and to the possible concomitant occurrence of non-volcanic processes. Since such bedforms appear relatively common along presently active systems, their recognition in ancient rock records (see for example Van den Berg & Lang, 2021) should be facilitated by this dataset, which is fundamental also for a preliminary evaluation and prediction of submarine geohazard in various eruptive centres worldwide.

The largest set of articles in this collection is represented by works focussing, at least in part, on analyses of stratigraphic records from rock outcrops and shallow-subsurface datasets. As mentioned above, cyclic steps occur prominently in the literature as the most frequently treated supercritical bedform encountered in numerous studies of subaqueous density flows. However, due to our limited ability to reproduce experimentally the accumulation and preservation of cyclic-step deposits at the large scales of their common occurrence in nature, knowledge of these features is still in its infancy. Englert *et al.* (2021) collate bathymetric surveys and core data from presently active cyclic steps along the slopes of the Squamish River delta (British Columbia, Canada) and of Monterey Canyon (California, USA) to refine conceptual models on the three-dimensional evolution and internal facies distribution of cyclic-step strata attaining scales of tens to hundreds of metres. Insights are applied to the interpretation of Cretaceous deep-water successions of the Nanaimo Group (British Columbia) showing a convincing comparability in terms of facies and architecture that will contribute to inform the identification of variably preserved cyclic-step strata in other stratigraphic records. Ghienne *et al.* (2021) present bathymetric observations of crescent-shaped bedforms accreting on modern meltwater-fed delta slopes of Baffin Island (northern Canada). Upslope migration as revealed by repeat surveys suggests an interpretation of these bedforms as cyclic steps maintained by turbidity currents. Cores collected from one of the bedforms in this modern system are compared with the depositional facies exposed in Late Quaternary unconsolidated sands at Portneuf-Forestville (Québec), originated on an upper deltaic slope of a glaciofluvial system. Large composite scours filled-in by structureless pebbly sand with rip-up clasts and showing soft-sediment deformation are interpreted to be formed by high-density (stratified) turbidity currents generating dominantly erosional cyclic steps. More frequently, unstratified turbidity currents probably developed supercritical flow conditions within the antidunal bedform range, reworking the pre-existing cyclic-step topography, depositing well-bedded suites of top-cut-out turbidites which comprise the bulk of the stratigraphic record. This dual-flow model of relatively infrequent cyclic-step development and more common antidunal aggradation draping the cyclic-step morphology sheds new light on the dynamics of glaciofluvial delta slopes and on the interpretation of spatial facies transitions in subaqueous supercritical-flow deposits. Van den Berg & Lang (2021) present a detailed analysis of a rare outcrop example of cyclic-step deposits preserved in Miocene volcaniclastic sediments of southern Spain, formed along ancient subaqueous volcanic slopes, a setting that has been recognized by other authors as a favourable one for the generation of these bedforms (e.g. Casalbore *et al.*, 2014; Clare *et al.*, 2018). In addition, they provide a possible method for the quantitative reconstruction of bedform (palaeo)morphometry combining measures of architectural attributes from the studied succession with gradient estimates of the original depositional slope. From the stratigraphic record of terrestrial environments, Melstrom & Birgenheier (2021) describe the process sedimentology and architecture of lacustrine mouth-bar complexes of the Eocene Green River Formation exposed in the Uinta

Basin of Utah (USA), confirming the relevance of upper-flow-stage facies associations to palaeoclimatic interpretations of fluviodeltaic successions. Enhanced climate seasonality in the region during the Early Eocene Climatic Optimum triggered sediment-laden, ephemeral fluvial discharge events that are recorded in stratal signatures of transcritical to supercritical flow stages in proximal to medial subaqueous portions of lake-margin deltas, where greater accommodation allowed for better preservation potential. The greater runout potential of energetic outflows probably lies at the origin of elongate mouth-bar complexes that extended over relatively great distances from the shorelines. A modern environmental analogue for the Eocene deposits of Utah and their (palaeo)climatic implications is documented by Tan & Plink-Björklund (2021), who discuss the sedimentology of dry river-bed deposits and its inferred relationships to the architecture of subsurface deposits in a linked fluvial to shallow-lacustrine clastic system from Lake Daihai, Inner Mongolia (northern China), combining observations from shallow trenched and ground-penetrating radar. In a semiarid setting affected by strongly seasonal precipitations, the facies evidence for ephemeral high-discharge events is expressed at different scales both in river-channel and in delta-front deposits. The latter preserve evidence of possible cyclic-step facies generated by sustained riverine underflows, and expressed in different ways in proximity of the river mouth and, more distally, within the basal portions of deltaic foresets. Slootman *et al.* (2021) provide a rare in-depth discussion of a possible depositional model for sedimentary structures produced by chute-and-pool bedforms under high aggradation rates in shallow-marine settings. Chutes-and-pools remain the most poorly characterized bedforms within the supercritical range, and their genesis at the transition between antidunes and cyclic steps might imply that they represent a transient morphodynamic stage, rather than a stable bedform type. While their recognition has always been particularly rare and ambiguous from subaerial open-channel-flow deposits, due to the relatively scarce preservation potential in alluvial settings (with notable exceptions for deposits of catastrophic jökulhlaup events; e.g. Duller *et al.*, 2008), the shallow-marine example reported by Slootman *et al.* shows that in high-accommodation environments subject to elevated depositional rates these structures may produce facies signatures distinguishable from those of antidunes and cyclic steps. The outcrop examples of Postma *et al.* (2021) from Eocene channel-lobe transitions at the terminal portion of deltas in north-east Spain, show additional examples of possible chute-and-pool facies signalling complex flow transitions within the supercritical spectrum in density currents that aggraded antidunes and cyclic steps. Their high-resolution architectural analysis highlights the importance of defining architectural elements and hierarchies of stratal surfaces in unravelling the complexity of thick, highly heterogeneous supercritical facies associations. The article by Lang *et al.* (2021) provides an important overview of the many documented examples of supercritical-flow structures in glacigenic depositional environments, where high-discharge hydrological events are a common occurrence due to the inherent instability of mobile ice masses and ice-dammed or moraine-dammed waterbodies. Upper-flow-stage phenomena have been frequently reported from successions accumulated in glacial settings, but the number of well-constrained case studies has been increasing recently, offering the particularly important opportunity to compare sedimentary products of supercritical open-channel flows and density currents within deposits from the same ice-marginal settings, where the large volumes of displaced sediment guarantee a relatively greater preservation potential compared to other depositional environments. Other settings that have been traditionally associated with supercritical flow states are volcanic ones, where explosive eruptions may trigger catastrophic, high-density, high-velocity mixtures of gas and debris. However, recent evidence suggests that recognition of volcaniclastic facies formerly attributed to antidunes and chutes-and-pools may need to be revised in some instances. The article by Douillet (2021) suggests caution in the uncritical reliance upon supercritical facies models and in the application of inconsistent descriptive terminologies in the analysis of successions accumulated by pyroclastic density currents. High temperatures, high densities and localized phase transitions in these complex granular flows can lead to generation of superficially similar facies under physically rather diverse conditions, for which interpretations purely in terms of Froude number should be considered simplistic at the current state of knowledge.

The editors of this thematic issue are grateful to *Sedimentology*'s editorial and production staff (Peir Pufahl, Ian Kane, Giovanna Della Porta and

Elaine Richardson) for their continuous assistance and motivation toward bringing this compilation to successful publication. Many referees offered valuable expertise and insights to improve the contents presented herein, which we hope will motivate other colleagues to acquire greater interest in the sedimentology and dynamics of supercritical flows.

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Manuscript received 22 March 2021; revision accepted 13 April 2021