Build-up-and-fill structure: The depositional signature of strongly aggradational chute-and-pool bedforms

Arnoud Slootman *College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia – arnoudslootman@gmail.com*
Matthieu J.B. Cartigny *Department of Geography, Durham University, Durham, United Kingdom – matthieu.j.cartigny@durham.ac.uk*
Age J. Vellinga *National Oceanography Centre, University of Southampton Waterfront Campus, Southampton, United Kingdom – age.vellinga@gmail.com*

ABSTRACT: Chute-and-pools are unstable, hybrid bedforms of the upper flow-regime, populating the stability field in between two stable end-members (antidunes and cyclic steps). Chute-and-pools are manifested by supercritical flow (chute) down the lee side and subcritical flow (pool) on the stoss side, linked through a hydraulic jump in the trough. The associated sedimentary structures reported here were generated at the toe-of-slope of a Pleistocene carbonate platform dominated by resedimentation of skeletal sand and gravel by supercritical density underflows. It is shown that wave-breaking on growing antidunes occurred without destruction of the antidune like commonly observed for antidunes in subaerial flows. This led to the formation of chute-and-pools that were not preceded by intense upstream scouring, interpreted to be the result of high bed aggradation rates. The term *aggradational chute-and-pool* is proposed for these bedforms, associated with *build-up-and-fill structures* consisting of interstratified convex-upward (in-phase wave regime) and concave-upward (hydraulic jump regime) lenses.

1 INTRODUCTION

The upper flow-regime spans between two stable bedform end-members: short-wavelength antidunes and long-wavelength cyclic steps (wavelength measured relative to flow thickness) (Spinewine et al. 2009; Kostic et al. 2010; Yokokawa et al. 2016). Antidunes form under in-phase (standing) waves, whereas cyclic steps are marked by the permanent presence of hydraulic jumps in the troughs between successive steps (Taki and Parker 2005; Fildani et al. 2006; Cartigny et al. 2011).

A continuum of hybrid bedforms exists between the two end-members of the upper flow-regime (Yokokawa et al. 2011; Cartigny et al. 2014). Such hybrid bedforms develop in trains of antidunes affected by the occasional breaking of in-phase waves. In the unstable antidune regime, the surges that follow wave breaking perish rapidly. In contrast, surges in the chute-and-pool regime evolve into transient hydraulic jumps (Alexander et al. 2001; Cartigny et al. 2014).

The flow pattern in chute-and-pools mimics the flow between two successive crests in a series of cyclic steps, characterised by a Froude-supercritical chute down the lee side and a pool filled with Froude-subcritical flow on the stoss side (Simons et al. 1965; Hand 1974; Taki and Parker 2005). The transition from the supercritical to the subcritical regime is situated in the upstream region of the pool and is embodied by the hydraulic jump. In contrast to cyclic steps, the pool of chute-and-pools is progressively filled and the hydraulic jump is eventually flushed downstream.

Chute-and-pool bedforms are often associated with the formation of scour-and-fill structures (Hand 1974; Alexander et al. 2001; Lang and Winsemann 2013; Cartigny et al. 2014). On the basis of outcrops situated along the toe-of-slope off a carbonate platform covered with skeletal debris, this paper advocates that chute-and-pools generate *build-up-and-fill structures* under high aggradation rates.

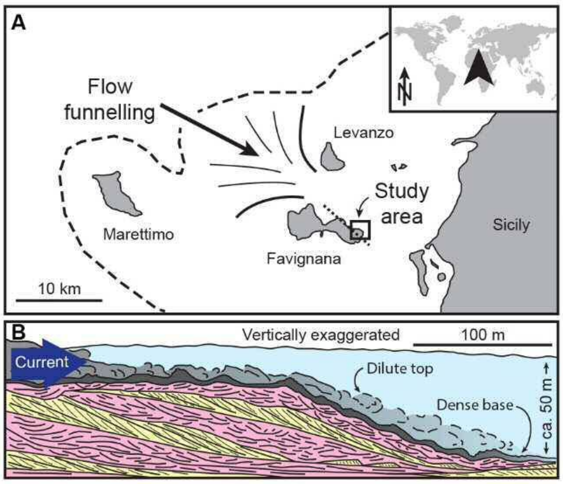

Figure 1. (A) The studied outcrops are located in the Egadi Archipelago in the Central Mediterranean Sea offshore western Sicily. Eastward flows were funnelled over a cool-water carbonate platform between the palaeo-islands Favignana and Levanzo during the Lower Pleistocene. Dashed line shows present-day 200 metres isobath. Stippled line indicates location of the cross-section. (B) Off-platform transport of skeletal debris was bimodal, hence progradation of the platform slope generated a repeated alternation of two types of clinoform units: (1) Numerous low-energy events formed up-to-10-m-thick stacks of subaqueous dune deposits (shown in yellow). (2) Single high-energy events produced Froude-supercritical density flows that deposited up-to-6-m-thick beds composed of sedimentary structures formed by upper flow-regime bedforms (shown in pink). The *build-up-and-fill structures* in these beds are the topic of the present study.

2 STUDY AREA

The studied sedimentary structures are located in the Lower Pleistocene calcirudites and calcarenites of Favignana Island; the largest island of the Aegadian Archipelago offshore western Sicily in the Central Mediterranean (Fig. 1). Continuous sea cliffs show that these heterozoan remains (*sensu* James 1997) adopt a large-scale clinoform architecture consisting of southeastward prograding units up to 50 m high, 500 m long, several m thick and dipping 5-20 degrees (Fig. 1).

The series of clinoform units is marked by a bimodal facies stacking pattern consisting of an alternation of bioturbated subaqueous dune deposits and thick supercritical density flow beds, which occur in approximately equal proportions (Slootman et al. 2016). Flow funnelling between the palaeo-islands during high-energy events (e.g. tsunamis) is suggested to have swept the platform and to lie at the origin of the large-scale sediment density flows (Slootman et al. in review).

Palaeoflow direction of the supercritical density flows is inferred from the orientation of the base and top of the beds, and compares well with the southeastward migration direction of subaqueous dunes, which is more straightforward to interpret.

3 BEDFORM RECONSTRUCTION

Line drawing of the internal stratification of density flow beds enabled the geometrical analysis at lamina-level, which forms the basis for the reconstruction of the timewise evolution of bed topography and the development of bedforms. This revealed the concept of the composite erosion surface and the alternation of convex-up and concave-up stratified lenses forming the main architectural elements of density flow beds. Two beds in two different exposures are presented.

3.1 Bed C27 in Balena outcrop

3.1.1 Observations

Convex and concave lenses. Bed C27 (ca. 2 m thick) is underlain and overlain by fossil subaqueous dunes. A downstream-dipping erosion surface dissects the section into two parts (Fig. 2). Different stratification patterns define the main architectural elements of density flow beds: convex-up-stratified lenses and concave-up-stratified lenses (subunits 1-3 in Fig. 2)

Composite erosion surface and nature of stratification. The convex-up backset-beds of subunit 1 are slightly concave-up at their upstream termination, where laminae erode the underlying fossil subaqueous dune and truncate the laminae of subunit 3. Most laminae of subunits 1 and 2 also truncate the underlying lamina at its upstream end, generating a composite erosion surface (Fig. 2). The nature of the stratification varies. In subunit 3, laminae are relatively thin and well pronounced. On the downstream side of

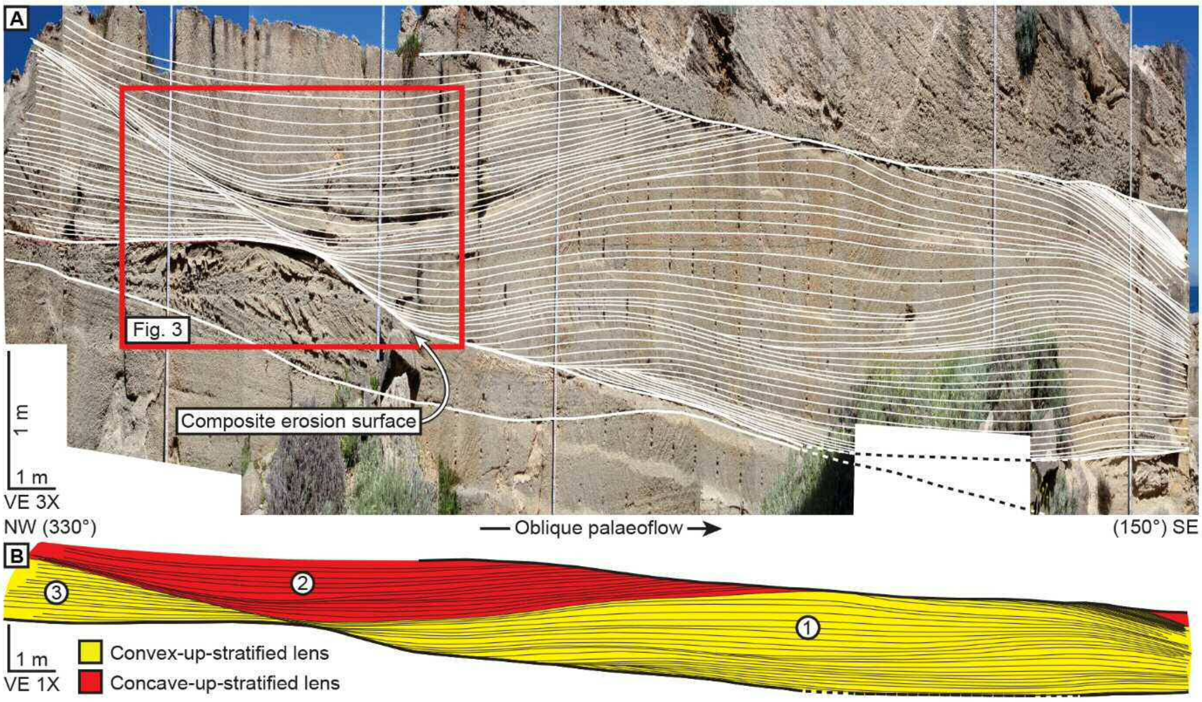

Figure 2. (A) Balena outcrop. Width of view is 24 m. Internal stratification of density flow bed C27 and bed boundaries are shown. Note the composite erosion surface at the upstream termination of strata. Three times vertically exaggerated. (B) Main architectural elements of bed C27. Subunits indicated by encircled numbers.

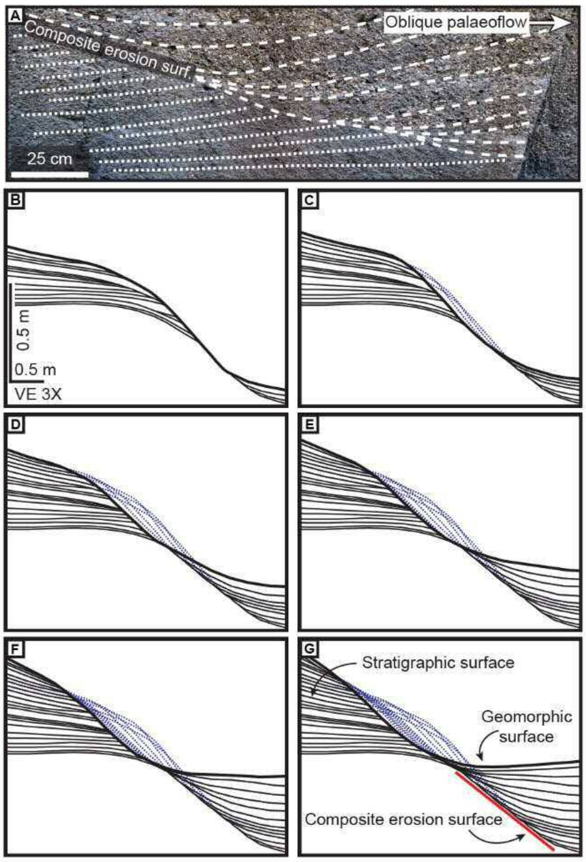

Figure 3. (A) Composite erosion surface juxtaposing the composite erosion surface, strata are calcirudites (left) with biogenic conglomerates (right). (B) Timewise reconstruction of bed-flow interfaces (geomorphic surfaces) in red box in Fig. 2.

invariably marked by an erosional lower boundary that commonly becomes less sharp toward the crest of the step, accompanied with a decrease in grainsize and an increase in sorting.

3.1.2 Interpretation

Strata correlation. A method useful for the correlation of strata is the 'barcode principle', which is based on the assumption that laminae have certain characteristics, such as relative thickness, grainsize distribution and sharpness of boundaries that can be used as a tracer along exposures. A high-frequency pulsation intrinsic to the flow led to a cyclic alternation of (in most cases) erosion and deposition related to the formation of individual laminae. A temporal variation in the intensity of such fluctuations and herewith the rate of deposition created a bar-code-like pattern in the deposit, occurring on both sides of (composite) erosion surfaces or even in different outcrops, albeit with a slightly different character depending on the local conditions of deposition.

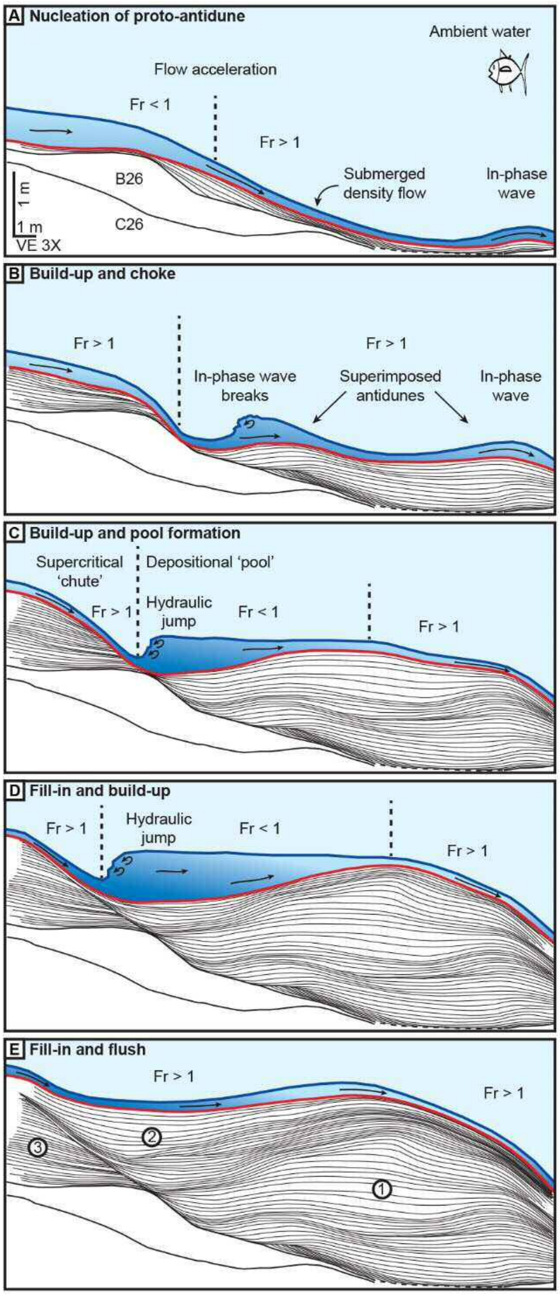

Figure 4. Morphodynamic reconstruction of the Balena outcrop and the evolution of the build-up-and-fill structure. See text for explanation.

The missing part of laminae comprised within the erosion surface can be inferred from the non-eroded portion.

Geomorphic surfaces. This introduces the concept of geomorphic surfaces (Sylvester et al. 2011), representing time lines of the bed-flow interface (Fig. 3). Geomorphic surfaces are key to the reconstruction of the morphodynamic evolution of bedforms. It is proposed that the foreset-beds of subunit 3 were continuous into the backset-beds of subunits 1 and 2 such that a convex-up step connected both sides. The concave-up portion that linked the upstream slope with the downstream step was thus the trough of a bedform, which migrated upward by deposition on the stoss-side and upstream by erosion of the lee side. This style of deposition is characteristic of a hydraulic jump on an aggrading mobile substrate (e.g. Alexander et al. 2001; Duller et al. 2008; Cartigny et al. 2014; Dietrich et al. 2016). Hydraulic-jump-related deposition was preceded by the build-up of the step and succeeded by the infill of the trough, altogether generating the build-up-and-fill structure.

Bedform evolution. The evolution of the build-up-and-fill structure is reconstructed by the stepwise stacking of laminae, reconstructed using the bar-code principle. The bed went through the following five phases (Fig. 4): (a) Nucleation: establishment of an asymmetrical proto-antidune under an in-phase wave. (b) Build-up and choke: the antidune developed into a long-wavelength step superimposed by two short-wavelength antidunes. As the short-wavelength antidune at the upstream side built-up, the overriding flow thickened because supercritical flows tend to amplify the topography of the bed. Such thickening co-occurred with flow deceleration, until the densimetric Froude number fell below unity. The transition from supercritical to subcritical flow at the crest of the antidune, involved the breaking of the in-phase wave and the formation of a hydraulic jump (flow-choking, e.g. Fedele et al. 2017). Retention of water in the hydraulic jump reduced the discharge over the second superimposed antidune, which led to the build-up and subsequent breaking of the overriding in-phase wave. (c) Build-up and pool formation: the two antidunes progressively merged into a single, large step governed by asymmetrical deposition over its entire length that resulted in its vertical growth. The trough between the 'chute' and the crest of the step developed into a ‘pool’ by the accumulation of water, herewith enhancing the intensity of the hydraulic jump. The configuration now established is referred to as a chute-and-pool. Deposition from the hydraulic jump induced the upward migration of the trough, whereas erosion by the chute forced the trough to migrate upstream. This continued the creation of the downstream-dipping composite erosion surface, the formation of which already started in the antidune configuration. (d) Fill-in and build-up: the trough filled with sediment as a result of deposition rate in the trough outpacing that on the crest. Erosion no longer governed the chute, which had become depositional, herewith overstepping the composite erosion surface. (e) Fill-in and flush: the depth of the trough abated and the trough eventually disappeared. Deceleration of the chute no longer caused the transition to subcritical flow and the hydraulic jump was flushed downstream, re-establishing supercritical flow conditions throughout.

3.2 Bed C28 in Pappagallo outcrop

3.2.1 Observations

Bed C28 reaches over 7 m and is underlain by two fossil subaqueous dunes in the Pappagallo outcrop. Reconstruction using the barcode-principle reveals the continuity of some laminae over the entire ca. 60 m length of the outcrop, enabling the reconstruction of a few key geomorphic surfaces thus representing time lines (encircled numbers in Fig. 5). Laminae with an upward-decreasing concavity overlie the upstream subaqueous dune. This concave-up lens evolves upward into a near-horizontal bed (1) and then into a convex-up shape (2), which grades downstream into another concave fill (top of which is 3). The thickness of lenses may be strongly reduced in upstream direction from a few metres down to a few tens of cm or less. The marked timelines illustrate that the ‘build-up’ and ‘fill-in’ phases alternate in a timewise sense. The build-up phase commonly initiates from a semi-horizontal surface (e.g. 1,3). The succeeding fill-in phase (partly) restores the near-horizontal bed (e.g. 3,5).

3.2.2 Interpretation

The stacked build-up-and-fill structures composing bed C28 in the Pappagallo outcrop reflect a periodicity in bedform behaviour: build-up and fill-in phases alternate in both horizontal and vertical direction (Fig. 5). The 3 m elevation drop over the lee side of the underlying fossil subaqueous dune at the upstream side (0) dictates that the first phase in this exposure is a fill-in phase. The composite erosion surface at the upstream limit of the concave lens suggests that a hydraulic jump was involved in its formation. A convex lens that formed during the subsequent build-up phase overlies the horizontal top of the concave lens (1). This pattern continues in horizontal and vertical direction, illustrating the periodic alternation of build-up and fill-in phases.

8 DISCUSSION AND CONCLUSIONS

There is a fundamental difference between antidunes and cyclic steps (Fildani et al., 2006; Spinewine et al., 2009; Kostic, 2010; Cartigny et al. 2014; Yokokawa et al. 2016). Antidunes are short-wavelength bedforms that develop under trains of in-phase surface waves. Cyclic steps are long-wavelength bedforms associated with series of steps marked by supercritical flow down the lee side and subcritical flow on the stoss side, separated by hydraulic jumps in the intervening troughs (e.g. Cartigny et al., 2011).

Hybrid bedforms that have more in common with cyclic steps than with antidunes are predominately characterised by hydraulic jumps and less so by in-phase waves.

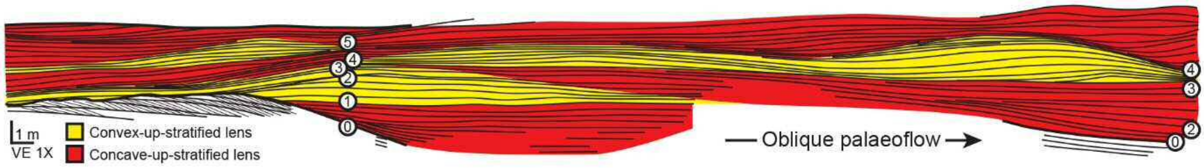

Figure 5. Main architectural elements bed C28 in the Pappagallo outcrop (58 m wide). See text for explanation.

This morphology is referred to as chute-and-pool (Simons et al., 1965) and is commonly associated with the formation of scour-and-fill structures.

The density flow beds of the Lower Pleistocene carbonate slope of Favignana Island are composed of *build-up-and-fill structures*, defined by interstratified convex and concave lenses as main architectural elements. On the basis of detailed morphodynamic reconstructions, it is suggested that convex lenses represent deposition under in-phase waves in the antidune-regime, and that concave lenses were formed by deposition from hydraulic jumps situated in the trough between bedforms. Such hydraulic jumps formed by the breaking of the in-phase antidune wave. Unlike wave-breaking in subaerial flows, wave-breaking was not accompanied with antidune destruction due to high rates of bed aggradation. Hence, the term *aggradational chute-and-pools* is proposed for these bedforms.

9 REFERENCES

Alexander, J., Bridge, J.S., Cheel, R.J. and Leclair, S.F. (2001) Bedforms and associated sedimentary structures formed under supercritical water flows over aggrading sand beds. Sedimentology, 48, 133-152.

Cartigny, M.J.B., Postma, G., Van den Berg, J.H. and Mastbergen, D.R. (2011) A comparative study of sediment waves and cyclic steps based on geometries, internal structures and numerical modeling. Mar. Geol., 280, 40-56.

Cartigny, M.J.B., Ventra, D., Postma, G. and Den Berg, J.H. (2014) Morphodynamics and sedimentary structures of bedforms under supercritical flow conditions: New insights from flume experiments. Sedimentology, 61, 712-748.

Dietrich, P., Ghienne, J.F., Normandeau, A. and Lajeunesse, P. (2016) Upslope-Migrating Bedforms In A Proglacial Sandur Delta: Cyclic Steps From River-Derived Underflows? J. Sediment. Res., 86, 113-123.

Duller, R.A., Mountney, N.P., Russell, A.J. and Cassidy, N.C. (2008) Architectural analysis of a volcaniclastic jökulhlaup deposit, southern Iceland: sedimentary evidence for supercritical flow. Sedimentology, 55, 939-964.

Fedele, J.J., Hoyal, D.C., Barnaal, Z., Tulenko, J., Awalt, S. (2017) Bedforms created by gravity flows. In: Budd, D., Hajek, E., Purkis, S. (Eds.), Autogenic Dynamics and Self-Organization in Sedimentary Systems. SEPM Spec. Pub., 106, 95-121.

Fildani, A., Normark, W.R., Kostic, S. and Parker, G. (2006) Channel formation by flow stripping: large-scale scour features along the Monterey East Channel and their relation to sediment waves. Sedimentology, 53, 1265-1287.

Hand, B.M. (1974) Supercritical flow in density currents. J. Sed. Petrol., 44, 637–648.

James, N.P. (1997) The cool-water carbonate depositional realm. In: Cool-water carbonates (Eds. N.P. James and J. Clarke), SEPM Spec. Pub, 56, 1-20.

Kostic, S., Sequeiros, O., Spinewine, B. and Parker, G. (2010) Cyclic steps: A phenomenom of supercritical shallow flow from the high mountains to the bottom of the ocean. J. Hydr-Environ. Res., 3, 167-172.

Lang, J. and Winsemann, J. (2013) Lateral and vertical facies relationships of bedforms deposited by aggrading supercritical flows: from cyclic steps to humpback dunes. Sediment. Geol., 296, 36-54.

Simons, D.B., Richardson, E.V. and Nordin, C.F. (1965) Sedimentary structures generated by flow in alluvial channels. In: Primary sedimentary structures and their hydrodynamic interpretation (Ed. G.V. Middleton), SEPM Sp. Pub., 12, 34-52.

Slootman, A., Cartigny, M.J.B., Moscariello, A., Chiaradia, M. and De Boer, P.L. (2016) Quantification of tsunami-induced flows on a Mediterranean carbonate ramp reveals catastrophic evolution. Earth Planet. Sc. Lett., 444, 192-204.

Slootman, A., De Boer, P.L., Cartigny, M.J.B., Samankassou, E. and Moscariello, A. (in review) Evolution of a carbonate delta generated by gateway-funnelling of episodic currents. Sedimentology.

Spinewine, B., Sequeiros, O.E., Garcia, M.H., Beaubouef, R.T., Sun, T. and Savoye, B. (2009) Experiments on wedge-shaped deep sea sedimentary deposits in minibasins and/or on channel levees emplaced by turbidity currents. Part II. Morphodynamic evolution of the wedge and of the associated bedforms. J. Sediment. Res., 79, 608.

Sylvester, Z., Pirmez, C. and Cantelli, A. (2011) A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture. Mar. Petrol. Geol., 28, 716-727.

Taki, K. and Parker, G. (2005) Transportational cyclic steps created by flow over an erodible bed. Part 1. Experiments. J. Hydraul. Res., 43, 488-501.

Yokokawa, M., Y. Takahashi, H. Yamamura, Y. Kishima, G. Parker and N. Izumi. (2011) Phase diagram for antidunes and cyclic steps based on suspension index, non-dimensional Chezy resistance coefficient and Froude number. In: Int. Assoc. Hydro-Envir. Engin. and Res., 7th RCEM Symposium, Beijing, China (2011), Proceedings, 1789-1794.

Yokokawa, M., Izumi, N., Naito, K., Parker, G., Yamada, T. and Greve, R. (2016) Cyclic steps on ice. J. Geophys. Res.-Earth, 121, 1023-1048.