Bedform successions formed by submerged plane-wall jet flows

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ABSTRACT: Jet flows, expanding from an orifice into a standing water body, are considered as scale-independent model for clastic depositional processes. We conducted 3D experiments with Froude supercritical jet flows, systematically varying several of the controlling parameters such as bed slope, grain size, and flow variables that define the initial densimetric Froude number. The initial inertia-driven jets evolved into gravity-driven flows by rapid expansion and deceleration, thereby forming scours, mouth bars and trains of bedforms. Hydraulic jumps were absent in the flow transition. The geometries of the mouth bar and bedforms were primarily controlled by the initial densimetric Froude number. Further control was exerted by the bed slope, sediment supply and grain sizes. Gravity-controlled processes rapidly take-over the control on the morphodynamic evolution of the flow and are responsible for deposition on the lee side of the mouth bar and beyond.

1. INTRODUCTION

Jet flows are flows that emerge from an orifice into a standing water body and decelerate and expand due to the entrainment of ambient water. They can be considered as a basic model for clastic depositional processes independent of scale and environment, for example deltas (Bates, 1953), submarine fans (Beaubouef et al., 2003; Hoyal et al., 2003; Terlaky et al., 2016) and subaqueous ice-contact fans (Powell, 1990; Russell & Arnott, 2003; Winsemann et al., 2009). The evolution from inertia-driven jet flows into gravity-driven density flows is primarily controlled by the initial momentum and the density difference between the flow and the ambient water (Powell, 1990; Hoyal et al., 2003). The rates of jet flow deceleration and expansion and the expansion angle are primarily controlled by the orifice densimetric Froude number (Fr’). Secondary controlling factors for jet flows and their deposits include discharge, sediment concentration and grain size (Bates, 1953; Powell, 1990; Hoyal et al., 2003). Jet flows and their deposits display a distinct proximal to distal zonation. Jet-flow deposits are generally characterized by a mouth bar that develops downflow of a scour. The downflow facies tracts reflect the deceleration of the flow and pass from a region of by-pass and erosion via a region of bedform formation into a region of suspension settling (Powell, 1990; Hoyal et al., 2003; Russell & Arnott, 2003; Winsemann et al., 2009). After the transition from an inertia-driven jet flow into a gravity-driven density flow, the density flow may either evolve into an underflow or rise as a buoyant plume, depending on the density difference to the ambient water (Powell, 1990).

2. 2 METHODS

We conducted 3D tank experiments with submerged plane-wall jet flows in an experimental domain, which comprised an 8 m long and 5 m wide plate placed in a 10 m long, 7 m wide and 2 m deep glass-walled tank (Fig. 1A). The evolving flows and de-

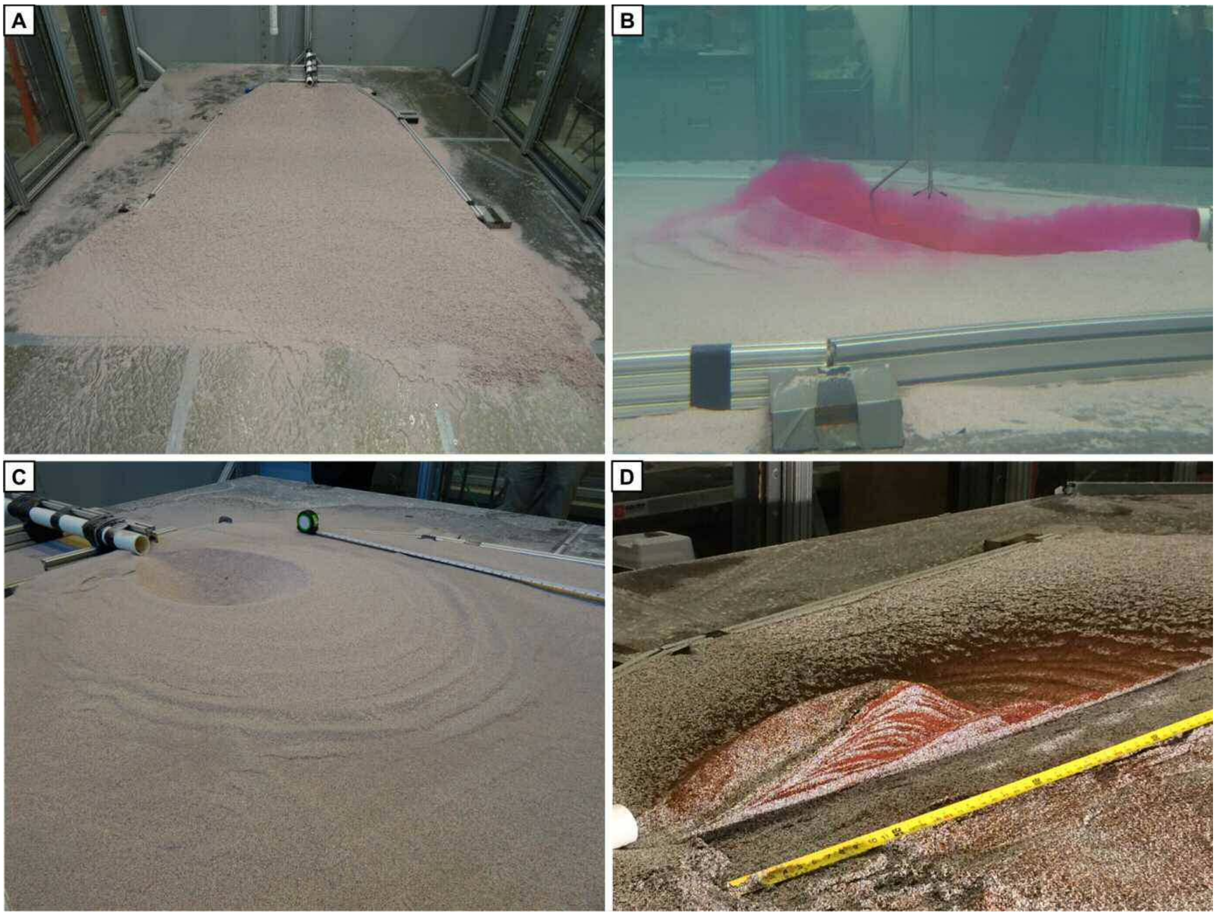

Figure 1. Experimental jet flows and their deposits. **A)** Experimental set-up for jet flows. A leveled sediment bed is prepared on the plate. Flows are released from the inlet pipe. **B)** The expanding jet flow forms a scour and a mouth bar (densimetric Froude number Fr'=4). Flows passing over the mouth bar have already evolved into gravity-controlled density flows. **C)** Sour and mouth bar of a experimental jet flow (Fr'=2). **D)** Cross-section of a jet-flow deposit (Fr'=4).

posits were documented by photographs through the tank walls. Velocity (point ADV and profiler) and density (conductivity) probes enabled the collection of flow data during the experiments. After the experiments the tank was drained and the external and internal geometry of the deposits was measured.

The controlling parameters were systematically varied to test their impact on the flow dynamics and the resulting deposits. These controlling parameters include bed slope, sediment-grain size and the flow variables (discharge, density difference and pipe diameter) that define the initial densimetric Froude number. The tested experimental conditions were classified as follows: (i) non-aggrading jet flows on non-erodible beds, (ii) non-aggrading jet flows on erodible beds, and (iii) aggrading jet flows on erodible beds.

3. 3 RESULTS

The initial inertia-driven jet flows evolved into gravity-driven density flows by rapid flow expansion and deceleration (Fig. 1B). The turbulent jet flows rapidly expanded from the orifice by the entrainment of ambient water into large turbulent eddies that develop at the flow interface. Hydraulic jumps were never observed in the expanding Froude supercritical jet flow or at the transition into a density flow. The transition from jet to density flow was observed to occur at a short distance from the orifice, typically at the crest of the evolving mouth bar.

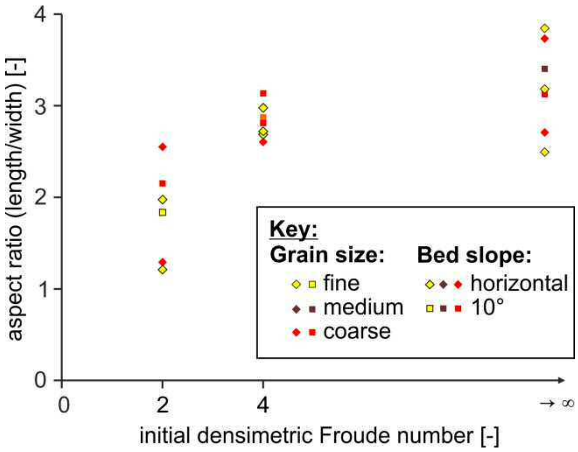

Figure 2. Aspect ratio (length/width) of the mouth-bar crest plotted against the initial densimetric Froude number.

The decelerated density flow was pushed away by the jet flow, promoting the formation of an underflow (Fig. 1B). Underflows were observed to flow all the way to the distal margins of the plate. In experiments with low-density jet flows, a rise of a buoyant plume was observed. However, rising plumes were also observed to develop from high-density jet flow.

Successions formed by the experimental flows comprised early-stage bedforms, scours and mouth bars and bedforms deposited by the distal density flow (Figs. 1C). Concentric early-stage bedforms commonly preceded the formation of the scour and mouth bar. The formation of these bedforms was very rapid and occurred within few minutes after the start of the flow or sediment feed, respectively. The geometry of the bedforms was primarily controlled by the densimetric Froude number. The aspect ratio (length vs. width) of the bedforms crests increased with increasing densimetric Froude number, displaying a logarithmic-style trend (Fig. 2). During the experiments the early stage bedforms showed an interaction with the flow thickness, indicating that they represent small-scale dunes (Fedele et al., 2017).

The formation of scours and mouth bars was observed in all experiments with erodible beds, regardless if sediment was fed into the jet or not. The geometry and dimensions of the scour and mouth bar were controlled by the initial densimetric Froude number, the sediment-grain size and the sediment supply. The aspect ratio (length vs. width) was controlled by the densimetric Froude number and increased with higher Froude numbers (Fig. 2). The depth of the scour increased with decreasing densimetric Froude number and more gravitationally-dominated flows. The mouth-bar height increased with increasing scour depth and was therefore also controlled by the densimetric Froude number. Experiments with aggrading jet flows led to the vertical and lateral growth of the mouth bar and an infilling of the scour (Fig. 1D). The dimensions and steepness of the mouth bar and bedforms were further related to the sediment-grain size with coarser grain sizes causing the formation of higher and steeper bars and bedforms. Internally, mouth bars were characterized by prograding foreset-like geometries (Fig. 1D).

Very low-relief rounded bedforms were observed to form on the distal slope of the mouth bar, where the flow had transitioned to a fully gravity-dominated density flow. The rounded bedforms on the mouth-bar front appeared to be in-phase with the density flow. On horizontal plates the mouth-bar deposits passed distally into the early-stage bedforms. The movement and growth of these bedforms was very slow and they were starved of sediment, receiving only a small fraction of sediment that bypassed the mouth bar. At high sediment supply the mouth bar prograded over the early-stage bedforms.

In experiments on inclined plates density flows were observed to flow all the way to the distal margins of the plate and led to the formation of small scours and bedforms between the base of the mouth bar and the distal margin of the plate, which were aligned along preferential flow pathways.

Bedform trains downflow of the mouth bar were prominent in runs with fine-grained sediment and low sediment supply, where mouth-bar aggradation was low. The proximal bedforms were symmetrical, while the distal bedform were asymmetrical with steeper lee sides. In plan-view the bedforms displayed straight crests. Superimposed onto these bedform trains smaller-scale asymmetrical bedforms occurred. Observations during the runs showed an in-phase relation between the bedform trains and the upper interface of the density flow, indicating that they represented antidunes (Fedele et al., 2017).

Bedform fields laterally adjacent to the mouth bar were prominent when coarse-grained sediment was supplied at high rates, leading to high mouth-bar aggradation and flow splitting around the mouth bar. The bedform trains comprised scours separated by low symmetrical bedforms, which were laterally followed by asymmetrical bedforms. An in-phase relation with the upper flow interface indicates that these bedforms represent antidunes (Fedele et al., 2017).

4 IMPLICATIONS FOR FIELD STUDIES

Glacigenic jet flows triggered by the release of meltwater at the grounding line of a glacier can be considered as an ideal field example of plane-wall jet flows. Subaqueous ice-contact fan successions related to glacigenic jet flows are commonly characterized by deposits of aggrading supercritical flows (e.g., Russell & Arnott, 2003; Winsemann et al., 2009; Lang & Winsemann, 2013; Lang et al., 2017b). Depositional processes in glacigenic jet-flow settings have been deduced from outcrop-based studies. The proximal to distal zonation of glacigenic jet flows is reflected in the zonation of the sedimentary facies. Many sedimentary facies in subaqueous ice-contact fan successions indicate supercritical flows, hydraulic jumps and highly aggradational conditions. The most proximal fan zone is dominated by erosion and bypass of sediment. In the proximal fan, coarse-grained (gravel-rich) deposits display crude stratification and cross-stratification and are interpreted as pointing to the rapid infilling of scours. Winsemann et al. (2009) reconstructed large-scale (several km long, 10’s of meters deep) scours beneath the proximal parts of a Pleistocene glacilacustrine ice-contact fan, closely resembling the scours formed by the experimental jet flows. Distally, the deposits become more sand-rich and bedform successions are indicative of rapidly waning flows, including deposits of hydraulic jumps, antidunes and humpback dunes (Powell, 1990; Russell & Arnott, 2003; Winsemann et al., 2009; Lang & Winsemann, 2013; Lang et al., 2017b). Farther downflow, deposits indicate waning flow and deposition by migrating dunes, (climbing) ripples and suspension fall-out (Powell, 1990; Russell & Arnott, 2003; Winsemann et al., 2009). However, in field-based studies it may be ambiguous if deposits are derived from the glacigenic jet flow or the associated density flow (Lang et al., 2017b).

Gravity-driven density flows, which switch from confined to unconfined settings, may also be modeled as submerged plane-wall jets. Field examples of such expanding density flows occur across several orders of magnitude, including submarine fans, lobes and crevasse splays, where flows expand from the mouths of canyons, distributary channels and crevasse channels, respectively (Beaubouef et al., 2003; Hoyal et al., 2003; Terlaky et al., 2016). In these settings, density flows are prone to become supercritical and the resulting deposits are strongly affected by the flow morphodynamics. Erosion and deposition in the zone of flow expansion are commonly associated with the occurrence of bedforms indicating supercritical flow conditions (Postma et al., 2014, 2015; Hamilton et al., 2015, 2017; Lang et al., 2017a). The deposition of mouth bars in front of channels is strongly controlled by the densimetric Froude number within the channel (Hamilton et al., 2015, 2017).

4. 5 CONCLUSIONS

Our experiments show the rapid evolution from inertia-driven jet flows to gravity-driven density flows by flow expansion and deceleration. The results show that gravity-controlled processes rapidly take-over the control on the morphodynamic evolution of the flow and are responsible for deposition on the lee side of the mouth bar and beyond. The experiments indicate that hydraulic jumps are absent.

The experimental jet-flow deposits comprise early-stage bedforms, scours and mouth bars. Flows with higher incoming densimetric Froude numbers produced scours with larger aspect ratios (length vs. width). Conversely, the scours were deeper for lower incoming densimetric Froude numbers. Scours formed by the entrainment of sediment by turbulent eddies. The entrained sediment was typically flushed out of the scour to build a mouth bar around the scour margin. The aspect ratio and the depth of scours provide indicators for the flow conditions at the orifice. The dimensions and steepness of the mouth bar and bedforms were controlled by the sediment-grain size, with coarser grain sizes causing the formation of higher and steeper bars and bedforms. Bedforms developed beyond the mouth-bar crest were related to the density flow. Their formation was controlled by the bed slope, sediment-grain size and sediment supply.

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