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Autogenic avulsion, channelization and backfilling dynamics of debris-flow fans

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ABSTRACT

Alluvial fans develop their semi-conical shape by quasi-cyclic avulsions of their geomorphologically active sector from a fixed fan apex. On debris-flow fans, these quasi-cyclic avulsions are poorly understood, partly because physical scale experiments on the formation of fans have been limited largely to turbidite and fluvial fans and deltas. In this study, debris-flow fans were experimentally created under constant extrinsic forcing, and autogenic sequences of backfilling, avulsion and channelization were observed. Backfilling, avulsion and channelization were gradual processes that required multiple successive debris-flow events. Debris flows avulsed along preferential flow paths given by the balance between steepest descent and flow inertia. In the channelization phase, debris flows became progressively longer and narrower because momentum increasingly focused on the flow front as flow narrowed, resulting in longer run-out and deeper channels. Backfilling commenced when debris flows reached their maximum possible length and channel depth, as defined by channel slope and debris-flow volume and composition, after which they progressively shortened and widened until the entire channel was filled and avulsion was initiated. The terminus of deposition moved upstream because the frontal lobe deposits of previous debris flows created a low-gradient zone forcing deposition. Consequently, the next debris flow was shorter which led to more in-channel sedimentation, causing more overbank flow in the next debris flow and resulting in reduced momentum to the flow front and shorter runout. This topographic feedback is similar to the interaction between flow and mouth bars forcing backfilling and transitions from channelized to sheet flow in turbidite and fluvial fans and deltas. Debris-flow avulsion cycles are governed by the same large-scale topographic compensation that drives avulsion cycles on fluvial and turbidite fans, although the detailed processes are unique to debris-flow fans. This novel result provides a basis for modelling of debris-flow fans with applications in hazards and stratigraphy.

Keywords Alluvial fan, autogenic dynamics, debris flow, debris-flow fan, experiment.

INTRODUCTION

Alluvial fans are semi-conical depositional landforms that form where confined stream channels emerge from mountain catchments into zones of reduced transport capacity (Harvey, 2011); they generally develop their semi-conical shape by shifting their geomorphologically active sector radially by repeated avulsion from a fixed fan apex. Fluvially dominated (i.e. stream flow and sheet flow) alluvial fan evolution has been ascribed to both allogenic (extrinsic) processes, such as tectonics, climate and base-level changes (e.g. Ritter *et al.*, 1995; Hartley *et al.*, 2005; Harvey, 2005; Sohn *et al.*, 2007) and autogenic processes (e.g. Schumm *et al.*, 1987; Nicholas & Quine, 2007; Ventra & Nichols, 2014), which are intrinsic properties and dynamics of alluvial systems that cause them to shift laterally by avulsion (Beerbower, 1964). Autogenic formative dynamics have been recognized in a wide range of subaerial fluvial systems: single-thread meandering and anastomosing systems (e.g. Törnqvist & Bridge, 2002; Stouthamer & Berendsen, 2007; Hoyal & Sheets, 2009), braided-river type systems (e.g. Sheets *et al.*, 2002; Ashworth *et al.*, 2004 2007) and stream-flow-dominated fan deltas and alluvial fans (e.g. Schumm *et al.*, 1987; Kim & Jerolmack, 2008; Clarke *et al.*, 2010; Van Dijk *et al.*, 2012; Hamilton *et al.*, 2013). Additionally, autogenic dynamics have been identified on subaqueous fans emplaced by turbidites (e.g. Cantelli *et al.*, 2011; Straub & Pyles, 2012; Hamilton *et al.*, 2015). Nevertheless, autogenic formative dynamics have not yet been directly observed on mass-flow-dominated alluvial fans (i.e. mudflows and debris flows), which hampers the understanding of the spatio-temporal patterns of mass-flow fan formation.

It is generally difficult to isolate the influence of internal forcings from the influence of external forcings in natural environments. Timescales of lateral shifting or avulsion of active fan sectors, generally estimated to be on the order of 10^2 to 10^4 years (e.g. Field, 2001; Zehfuss *et al.*, 2001; Dühnforth *et al.*, 2007), are generally too long to allow direct observation. Moreover, equifinality (the formation of similar landforms by different sets of processes), the commonly chaotic architecture of alluvial fan successions and the lack of high-resolution dating methods applicable to terrestrial coarse-clastic deposits have limited the preservation of information and hampered detailed stratigraphic analyses (Ventra & Nichols, 2014). The use of experimental physical modelling can overcome some of these difficulties and provides a valuable technique for studying autogenic processes and their spatial and temporal variability during alluvial fan evolution, by eliminating extrinsic factors in a controlled laboratory environment. Fluvial fans and fan deltas have been studied extensively in small-scale experiments (e.g. Schumm *et al.*, 1987; Bryant *et al.*, 1995; Whipple *et al.*, 1998; Davies & Korup, 2007; Van Dijk *et al.*, 2009 2012; Clarke *et al.*, 2010; Hamilton *et al.*, 2013), while there have been very few experiments on mass-flow fans (Hooke, 1967; Schumm *et al.*, 1987; Zimmermann, 1991), explaining the current lack of understanding of the formative dynamics of mass-flow fans.

In a wide range of experimental fluvial fans, generic autogenic fan dynamics are governed by repeated alternations of aggradation by unconfined sheet flow, fanhead incision leading to channelized flow, channel backfilling and avulsion (e.g. Schumm *et al.*, 1987; Bryant *et al.*, 1995; Whipple *et al.*, 1998; Van Dijk *et al.*, 2009 2012; Clarke *et al.*, 2010; Hamilton *et al.*, 2013). Indirect evidence for the presence of similar dynamics on natural fluvial fans comes from Scott & Erskine (1994), who studied 12 similarly sized and neighbouring Australian alluvial fans fed by the same rain-triggered floods. The fans had various initial morphologies, ranging from trenched to completely untrenched. After the floods, the gradient and morphological adjustments differed between individual fans. Effects ranged from no change to trench incision or backfilling, depending on the initial morphology of the fans, suggesting that the spatio-temporal evolution of fluvial fans found in a wide range of experimental fluvial fans also occurs on natural fluvial fans. The quasi-cyclic formative dynamics of fluvial fans are driven by the process of topographic compensation (i.e. compensational stacking; Straub *et al.*, 2009).

Quasi-cyclic alternations of backfilling, avulsion and channelization appear to be common denominators in the formation of subaerial and subaqueous fans because flow is driven by gravity, and deposition is consequently favoured in topographic lows (e.g. Hooke, 1967; Schumm *et al.*, 1987; Cantelli *et al.*, 2011; Van Dijk *et al.*, 2012). Accordingly, there is evidence for the formation of mass-flow fans by quasi-cyclic alternations of backfilling, avulsion and channelization. Cyclic avulsion of the locus of deposition has been observed on experimental fans by alternating mudflows and fluvial flows (Hooke, 1967; Schumm *et al.*, 1987). Natural mass-flow fans have been observed to shift their active locus of deposition over time (Hooke, 1967; Suwa & Okuda, 1983). This is demonstrated by their typical semi-conical shape (Blair & McPherson, 1994 2009), the presence of active and long-inactive sectors (e.g.Wells *et al.*, 1987; Frankel & Dolan, 2007; De Haas *et al.*, 2014 2015c) and detailed reconstructions of depositional loci over time (e.g. Dühnforth *et al.*, 2007; Stoffel *et al.*, 2008; Colombera & Bersezio, 2011). Whether these dynamics are induced by allogenic or autogenic controls remains to be established. Yet, as the timescale of active sector avulsion on mass-flow fans (e.g. Dühnforth *et al.*, 2007; Stoffel *et al.*, 2008) is generally much smaller than the timescales associated with external forcings (e.g. Densmore *et al.*, 2007; Allen, 2008), autogenic dynamics are expected to govern avulsive cycles on natural mass-flow fans (Ventra & Nichols, 2014). Nevertheless, the drivers behind the quasi-cyclic alternations of backfilling, avulsion and channelization on mass-flow fans are currently poorly understood.

The main objectives of this study are to: (i) study the spatio-temporal patterns of debris-flow fan formation under constant extrinsic variables (i.e. constant debris-flow volume, sediment concentration and rheology); (ii) to provide insight into the processes that govern the autogenic formation of debris-flow fans; and (iii) to compare the formative dynamics of debris-flow fans to those on other fan types.

This paper is organized as follows. First, the layout and boundary conditions of the experimental flume and laboratory experiments are described. Then, the general evolution of autogenic cycles on one of the experimental debris-flow fans is described, and the processes that cause these cycles are detailed. Next, a conceptual model of autogenic dynamics on debris-flow fans is presented based on the present experimental results. This model is compared to previous experimental fans and to observations from natural fans. Finally, topographic compensation or compensational stacking as an emergent mechanism driving autogenic dynamics on all known fan types is discussed.

METHODS

Methodology

Five experimental fans were formed by feeding consecutive debris flows through a chute onto an outflow plain (Fig. 1, Table 1; Movies S1 to S5), using the experimental setup of De Haas *et al.* (2015a) that was previously used to study the effects of debris-flow composition on runout, depositional mechanisms and deposit morphology of individual debris flows. Each of the fans was formed by similar debris flows with constant composition and volume, as well as initial terrain topography (i.e. channel width, length and inclination and outflow plain inclination), to ensure that fan dynamics were governed by autogenic processes only. Between fans, the composition of the debris flows was changed (Fig. 2 and Table 1).

The fans were allowed to grow in size and slope until a maximum extent was reached, at which point subsequent debris flows were not able to reach the fan because they were blocked by accumulated debris in the feeder channel. As such, fans ranged in size from 19 to 55 stacked debris flows.

The debris flows were composed of clay (kaolinite), sand and basaltic gravel (Fig. 2 and Table 1). The dark-toned gravel conveniently highlighted textural patterns within the debris flows. Relative to the debris flows that were used to build fan 01 (reference sediment composition in De Haas *et al.,* 2015a), the debris flows varied in gravel fraction (fan 02), clay fraction (fan 03), water fraction (fan 04) and magnitude (fan 05) (Fig. 2 and Table 1).

All experimental debris flows were frictional flows, and comprised multiple surges (De Haas *et al.*, 2015a). Coarse particles were selectively transported to the flow front, and subsequently shouldered aside to form lateral levées (Fig. 3; Movie S10). This resulted in well-defined depositional lobes and lateral levées, wherein most coarse particles were concentrated in the levées and at the frontal flow margins.

After each debris flow, the fan was dried for at least 3 hours with a ventilator and a small heater. This was necessary because debris flows that retained a significant amount pore fluid were reactivated by subsequent debris flows, as also observed by Hooke (1967). Reactivation of debris-flow deposits rarely occurs on natural debris-flow fans because debris-flow return periods are generally in the order of months to decades (e.g. Van Steijn, 1996).

Fans 01, 02, 04 and 05 rapidly backfilled behind the initial deposits and into the channel, so that debris flows were not able to flow out onto the fan, and therefore the total number of debris flows was too small for well-developed autogenic cycles to occur (Movies S1 to S5). In contrast, fan 03 was formed by 55 debris flows and consequently two full autogenic cycles occurred on this fan. Therefore, only fan 03 is discussed in the *Results and Discussion* of this paper.

Experimental setup and data collection

The experimental flume consisted of a straight channel 2·0 m long and 0·12 m wide, with an inclination of 30° (Fig. 1), connected to an outflow plain with an inclination of 10°.

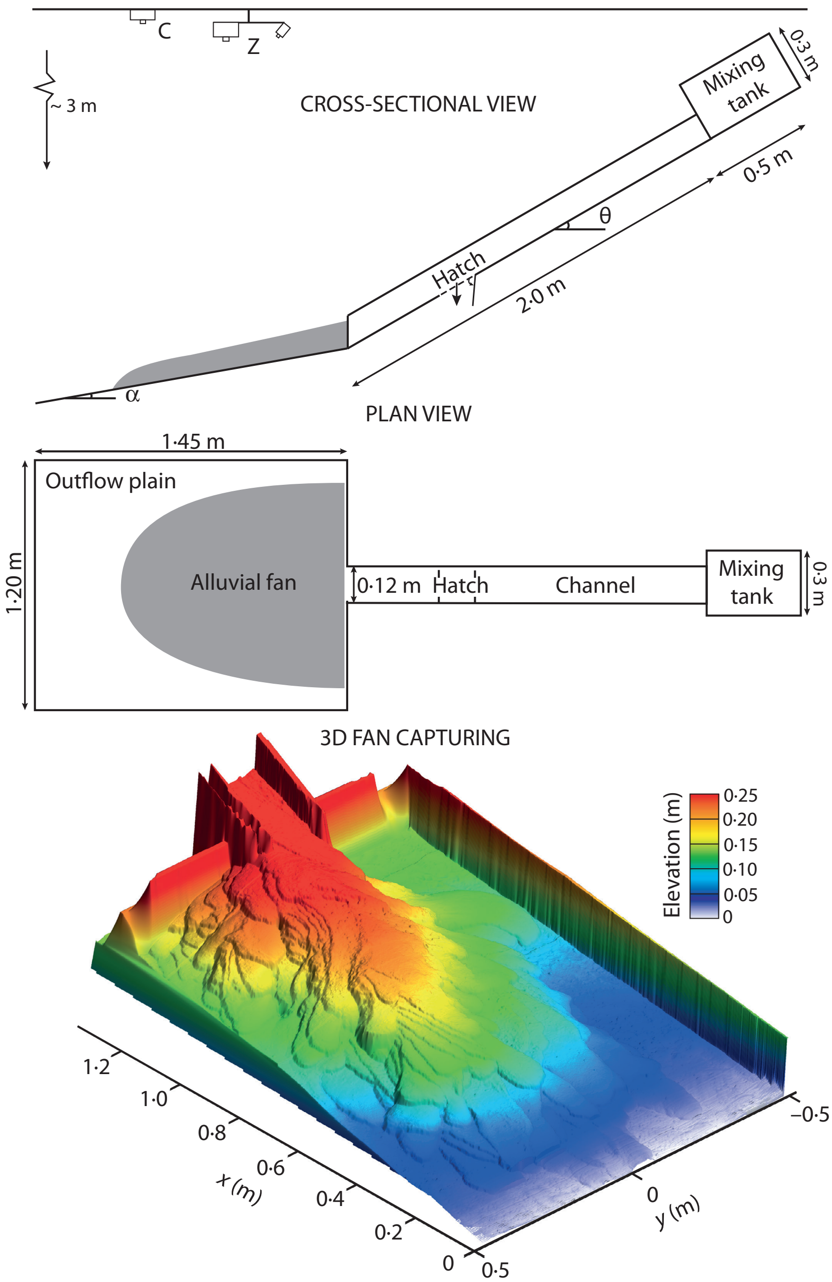

Fig. 1. Experimental flume setup. 'C' denotes the location of the camera, 'Z' denotes the z-Snapper three-dimensional scanner. The flume setup is similar to the setup used in De Haas *et al.* (2015a).

Upstream, the feeder channel was connected to a mixing tank with a gate from where well-mixed debris was released. To simulate natural bed roughness, the channel bed and sidewalls were covered with sand paper (grade 80; average particle diameter 0·19 mm), whereas the outflow plain was covered by a layer of *ca* 1 cm of unconsolidated debris (with a composition similar to the debris-flow composition). In the channel, a hatch was present 0·76 m above the transition from the channel to the outflow plain, a point termed the apex here. This hatch was opened electromagnetically 1·5 sec after release of debris from the mixing tank. Opening of the hatch resulted in diversion of the debris-flow tail, to prevent overflow and burial of the initial deposit. This was necessary because the small-scale experimental debris flows were relatively short in length, due to relatively high friction in small debris flows (De Haas *et al.*, 2015a).

Above the flume, a digital camera (Canon PowerShot A640; Canon Inc., Tokyo, Japan) was set up to image the debris-flow deposits. Videos of debris-flow movement and deposition on the fan were captured with a Canon Powershot A650 IS on a tripod directed obliquely at the channel and fan. Deposit morphology was measured at sub-millimetre resolution and accuracy after every debris-flow event using a Vialux z-Snapper 3D scanner (Vialux Messtechnik + Bildverarbeitung GmbH, Chemnitz, Germany) that captures a high-accuracy 3D point-cloud from a fringe pattern projector (Hoefling, 2004). Point clouds from the 3D scanner were processed with MATLAB® (The MathWorks, version 7.13.0.564) using natural neighbour interpolation to a gridded digital elevation model (DEM) of 1 mm resolution (Fig. 1).

Table 1. Initial and boundary conditions of investigated debris-flow fans.

Fan no.	01	02	03	04	05
No. of debris flows	19	22	55	32	15
D_{50} (mm)	0·39	0·50	0·37	0·39	0·39
Gravel fraction (vol%)	18	31	17	18	18
Sand fraction (vol%)	80	67·3	77·2	80	80
Clay fraction (vol%)	2·0	1·7	5·8	2·0	2·0
Water fraction (vol%)	44	44	44	47	44
Magnitude (kg)	6·5	6·5	6·5	6·5	9·8

The DEM was used to measure the debris-flow length, width, channel depth and fan slope. Fan slope was measured from the apex to maximum fan extent, following the active channel. Debris-flow length was defined as the maximum debris-flow runout from the apex, whereas width was defined as the maximum width of the depositional lobe. Channel depth was measured at an arbitrarily selected representative section of the channel, due to the longitudinal variation in channel depth. Debris-flow angle was defined as the average outflow angle of the debris flow on the fan relative to the channel.

During formation of the fans, the movable gantry of the z-Snapper 3D scanner unintentionally moved slightly upfan by a few millimetres per scan. Consequently, an increasing fraction of the fan toe was not covered. The DEMs were corrected for the displacement, and the missing section was reconstructed from elevation data obtained from previous scans. A transparent grey overlay shows the reconstructed section on the figures and movies, but note that the reconstruction does not affect any of the analyses performed here.

Potential scale effects

In small-scale experimental flume models, not all geometric features, kinematics and dynamics of natural systems are captured (e.g. Kleinhans *et al.*, 2014). Nevertheless, Hooke & Rohrer

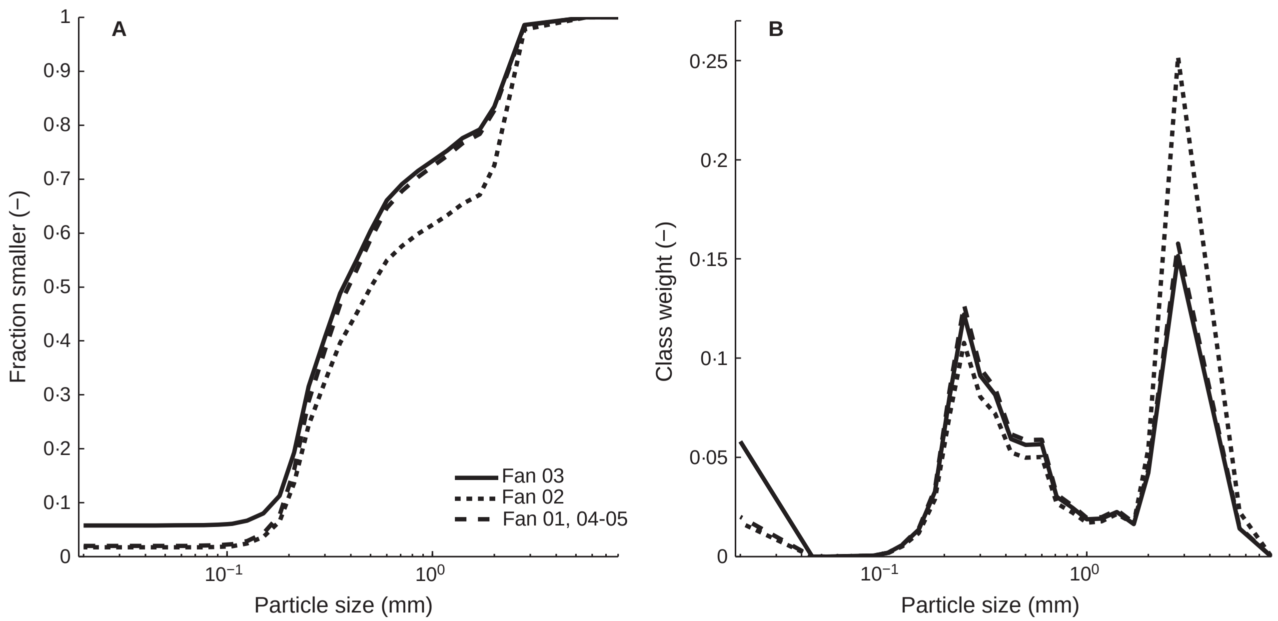

Fig. 2. Particle-size distribution of the debris flows used to build the debris-flow fans. (A) Cumulative distribution. (B) Frequency distribution.

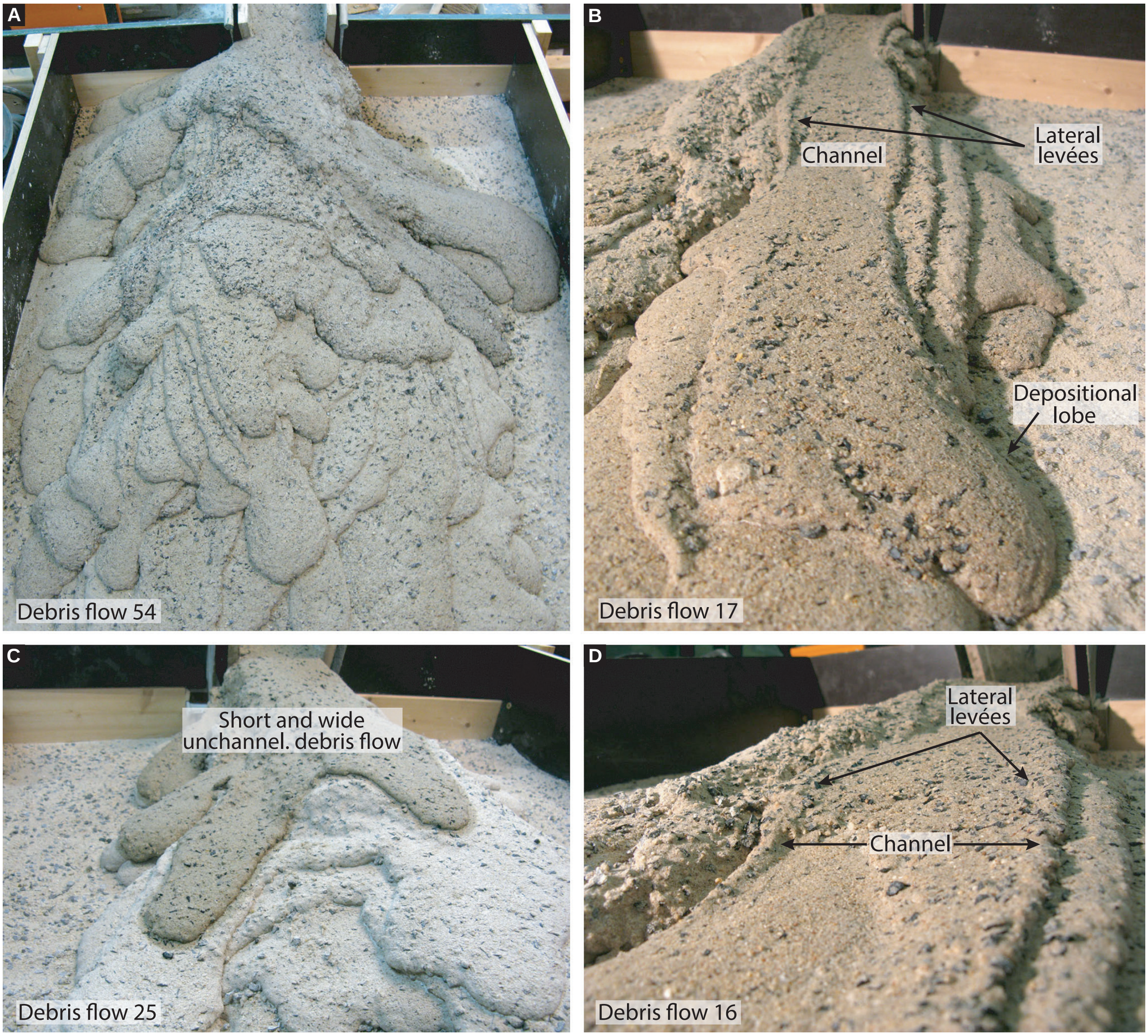

Fig. 3. Morphology and texture of the experimental debris flows on fan 03. (A) Morphology of the fully developed fan (debris flow 54). (B) Fan morphology in a channelized state, after debris flow 17. (C) Fan morphology in an unchannelized state prior to avulsion, after debris flow 25. (D) Detail of a channel on the fan, bordered by lateral levées (debris flow 16).

(1979) suggest that observations of processes on laboratory fluvial fans and their characteristics can still provide a basis for understanding of large-scale behaviour of natural fans (see also Hooke, 1967). As such, most fundamental current understanding of autogenic dynamics on fluvial fans stems from experimental fans (Postma, 2014). Likewise, the processes that govern autogenic dynamics on the present experimental debris-flow fan may be similar to the processes that govern the much less accessible dynamics on natural debris-flow fans. The current study aims to study the overall patterns and processes of autogenic debris-flow fan formation, which are probably less affected by potential scale effects than individual debris flows.

Small-scale experimental debris flows exhibit disproportionately large effects of yield strength, viscous flow resistance and grain inertia, while exhibiting disproportionately little effect of pore-fluid pressure (Iverson, 1997; Iverson & Denlinger, 2001; Iverson *et al.*, 2010). Nevertheless, the experimental debris flows described here do form lateral levées and distinct depositional lobes, and grain-size segregation results in accumulations of coarse particles in the lateral levées and frontal lobe margins, similar to natural debris flows. Moreover, De Haas *et al.* (2015a) showed that the channel width:depth ratio and runout area and distance of similar debris flows formed in the same flume were in the range of natural debris flows.

RESULTS

In this section, the morphology of experimental debris-flow fan 03 is first briefly described. Then, the general evolution of this fan, which was characterized by autogenic sequences, is described. Next, the mechanisms that were observed to drive the autogenic fan dynamics of channelization, backfilling and avulsion are detailed.

Fan and debris-flow morphology

The debris flows that formed the fan alternated between channelized flows bordered by lateral levées and short and wide unchannelled flows (Fig. 3). All debris flows had well-defined lobes with distinct edges and were generally up to a few centimetres thick. Lateral levées were self-formed and effectively conveyed the channelized flows (Fig. 3b,d). Levées were a few millimetres to *ca* 1 cm thick. Overall, fan morphology was characterized by shingled stacking of debris-flow lobes. Lobes covered the majority of the final fan surface, whereas the surficial contribution of channels was restricted (Fig. 3A). Longitudinal slopes roughly varied between 15° and 20°, the steepest lateral slopes in places exceeded 30°. This slope difference can probably be attributed to the inertia of the debris flows (Hooke & Rohrer, 1979).

Cycles of channelization, backfilling and avulsion

The first 10 debris flows deposited on top of one another and backfilled the initial debris-flow and flume channel (Movies S3, S6 and S9). The next debris flow avulsed left (looking down the transport direction) after which the first of two autogenic cycles was initiated (Figs 4 and 5; Movies S3, S6 to S9). Debris flows became progressively longer and more channelized until debris flows 16 to 19, after which they became progressively shorter and backfilled the channel until debris flow 25. During the retrograding phase, the area of main debris-flow deposition shifted slowly to the right side of the fan. Yet, avulsion only happened after complete backfilling of the channel. Starting from debris flow 26, the flows fully avulsed to the right side and the second autogenic cycle began. Debris flows 26 to 32 became progressively longer again, and a channel was formed on the proximal and medial domain of the fan. Debris flows 32 to 39 remained long and channelized, after which backfilling commenced once the accommodation in the distal domain was filled. Subsequent debris flows progressively retrograded and backfilled the channel until debris flow 52. Debris flow 53 then avulsed following the steeper slopes on the left side of fan. Debris flows 54 and 55 followed the same path. Fan formation was stopped after debris flow 55 because the feeder channel near the apex was completely filled.

In short, both autogenic cycles were characterized by the following phases: (1) First, the fan was in a channelized state. The proximal domain of the fan was channelized (Figs 3B, 3D and 4A), which caused the debris flows to deposit on the distal domain of the fan. Consequently, the channelized debris flows formed elongated deposits. (2) After maximum debris-flow length was reached, as limited by slope and debris-flow volume and composition, debris-flow runout progressively decreased (Fig. 4B). Successive debris flows became progressively shorter and wider, which caused in-channel deposition. Eventually, this led to very short and wide flows that completely filled the channel (Fig. 5). (3) After this, the debris flows avulsed towards the most preferential flow path on the fan, gradually forming a new channel over the course of multiple debris flows, until the debris flows became fully channelized again. The preferential flow path was defined by the balance between fan slope and flow inertia.

The first autogenic cycle lasted from approximately debris flow 10 to debris flow 25, while the second cycle lasted from debris flow 26 until debris flow 52 (Fig. 5). The second autogenic cycle thus consisted of more debris flows than the first cycle, 27 versus 15, respectively. This increase can be attributed to growing accommodation as the fan apex grew in elevation. Fan aggradation by debris-flow deposition occurred preferentially in topographic lows between older deposits, eventually leading to relatively uniform aggradation (i.e. topographic compensation or compensational stacking). The autogenic

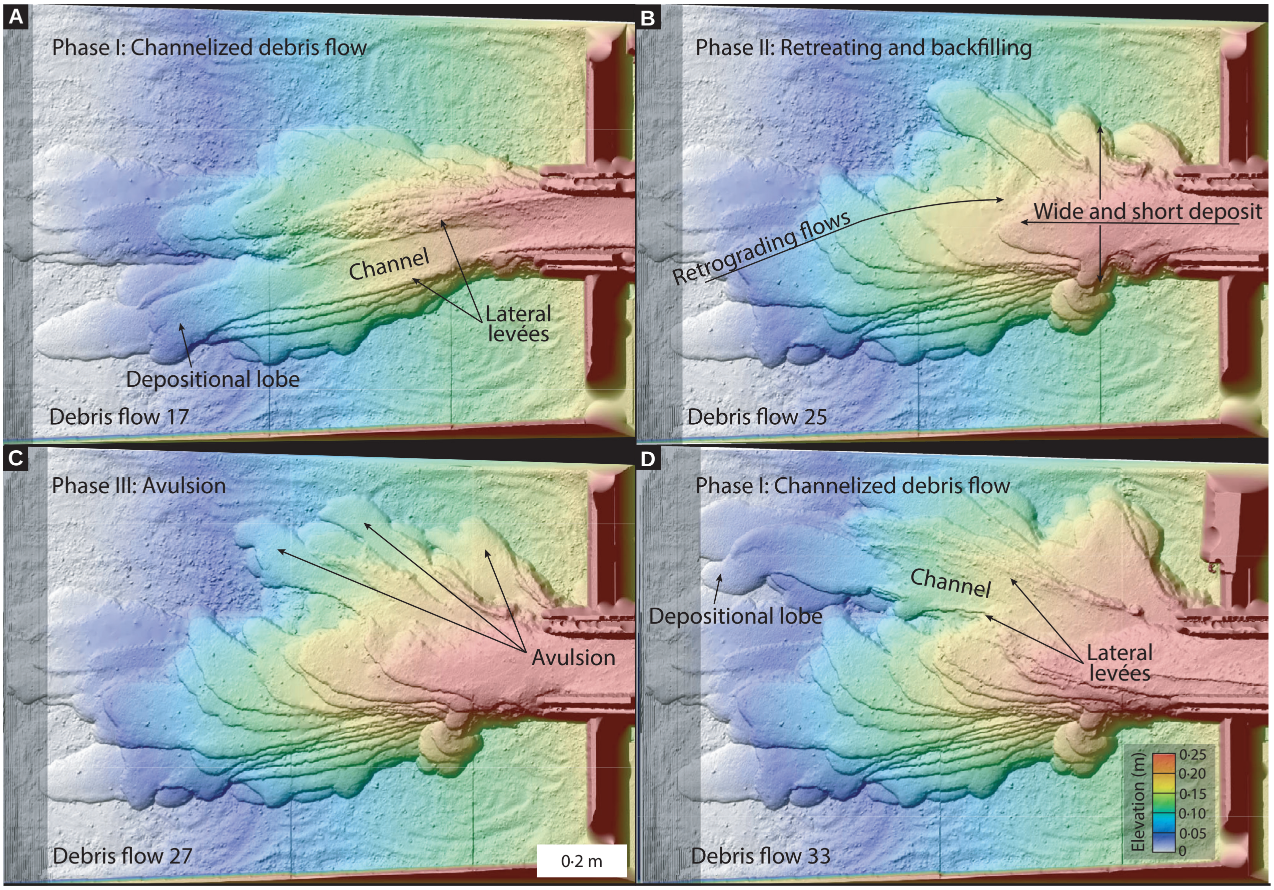

Fig. 4. Autogenic cycle on experimental debris-flow fan 03. (A) Channelized debris flow. A channel is present on the proximal and medial domain of the debris-flow fan, through which debris flows are conveyed to deposit on the distal domain of the fan. (B) Retreating and backfilling. After the debris flows have reached their maximum extent, backfilling commences. Debris flows become progressively shorter and wider until the channel is completely filled. (C) Avulsion. In the absence of an apex channel, the debris flows progressively avulse towards the most preferential flow path. (D) Channelized debris flow. After avulsion, the debris flows progressively channelize until the fan is in a fully channelized state again. See also Movie S7.

cycles were symmetrical: the prograding (channelization) and retrograding (backfilling) phases required a similar number of debris flows. In the second, longer autogenic cycle, the channel depth was larger because the channel was bounded by antecedent topography on its left side, and levées became stacked on the right side of the channel. Moreover, a subcycle was observed in the channelized phase (Fig. 5A). In this subcycle, the angle of deposition relative to the channel apex was shifted over the active sector of the fan, while the debris flows remained channelized. Both channelization and backfilling were gradual processes, requiring multiple debris flows to fully develop.

Within both autogenic cycles, the maximum and minimum debris-flow lengths were similar (Fig. 5B). At minimum, the debris flows had a length of 0·3 to 0·5 m, while maximum lengths were on the order of 1·2 m. Debris-flow width was inversely proportional to debris-flow length (Fig. 5B and C). In a fully channelized debris flow, channel width was similar to the width of the feeder channel (0·12 m), while the shortest and unchannelized debris flows had widths >0·4 m. The maximum widths prior to avulsion at the end of autogenic cycles 1 and 2 were similar (Fig. 5C). Channels were up to *ca* 1·5 cm deep, and channel depth was determined by levée formation in general (Fig. 5D). Average fan slopes along the active channel gradually increased from *ca* 10° to *ca* 18° while the fan grew in size until debris flow 25 at the end of autogenic cycle 1. In contrast, during autogenic cycle 2 slopes remained relatively constant (Fig. 5E). Finally, fan slopes strongly increased

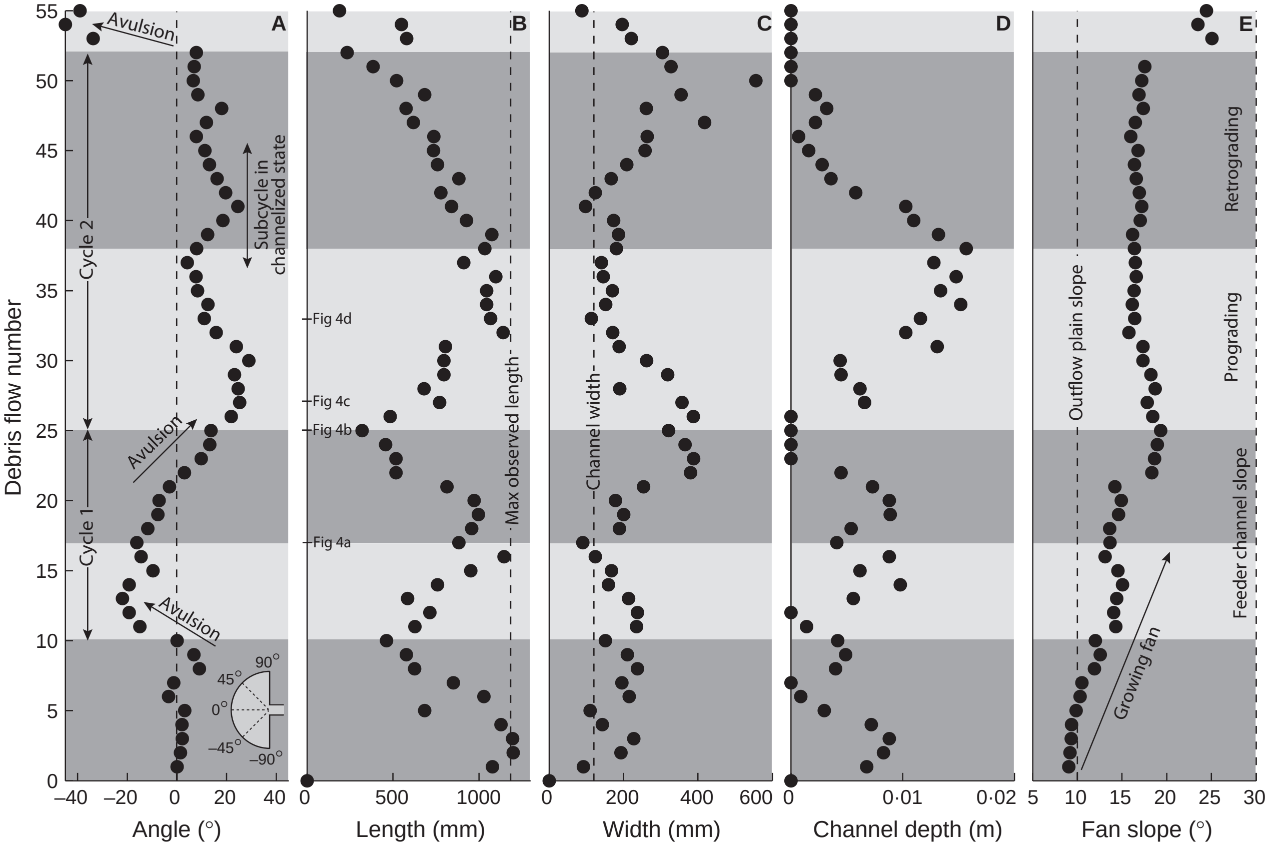

Fig. 5. Summary of the debris-flow characteristics within the autogenic cycles, during the formation of fan 03. Light and dark grey boxes indicate prograding and retrograding phases, respectively. (A) Debris-flow outflow angle relative to the feeder channel. (B) Debris-flow runout length, measured from apex to terminal lobe. 'Max observed length' refers to the maximum runout length of five similar debris flows over a uniform 10° sloping outflow plain (De Haas *et al.*, 2015a). (C) Debris-flow width. Dashed line indicates feeder channel width. (D) Channel depth, measured at an arbitrarily selected representative section of channel. Channel depth is mainly determined by levée thickness. (E) Average fan slope along the active debris-flow path. Dashed line indicates initial outflow plain slope.

after the avulsion at debris flow 53. In general, average fan slopes over the active debris-flow path were slightly lower in the channelized state than when debris flows were short, wide and unchannelized. In a channelized fan state, long profiles were relatively regular and constant, while during the retrograding phases, fan slope strongly increased in the proximal domain, mainly by the stacking of increasingly short debris flows (Fig. 6A). After avulsion, debris flows followed the preferential flow path and accordingly fan slopes were steep. As debris flows prograded and started to deposit debris on the distal fan, fan slopes decreased after which the cycle repeated itself.

The relation between fan morphology and autogenic dynamics on the experimental debris-flow fan was shown particularly well by the evolution of proximal fan cross-sections (Fig. 6B). After an initial phase of backfilling (A), the debris flows avulsed (B) and a phase of progradation and channelization occurred (C). Maximum debris-flow channel depth, as defined by levée height, developed in the longest debris flows, and peaked at *ca* 1 cm (Fig. 6B). The progradational phase then gradually changed to a retrograding phase (D), where debris flows backfilled the channel by in-channel sedimentation, until the channel was no longer defined and the upper part of the fan profile became plano-convex (debris flow 28 in Fig. 6B). Because of the plano-convex profile, the debris flows were not forced into a specified direction by the presence of a channel and freely avulsed following the preferential flow path (E), after which the cycle repeated itself.

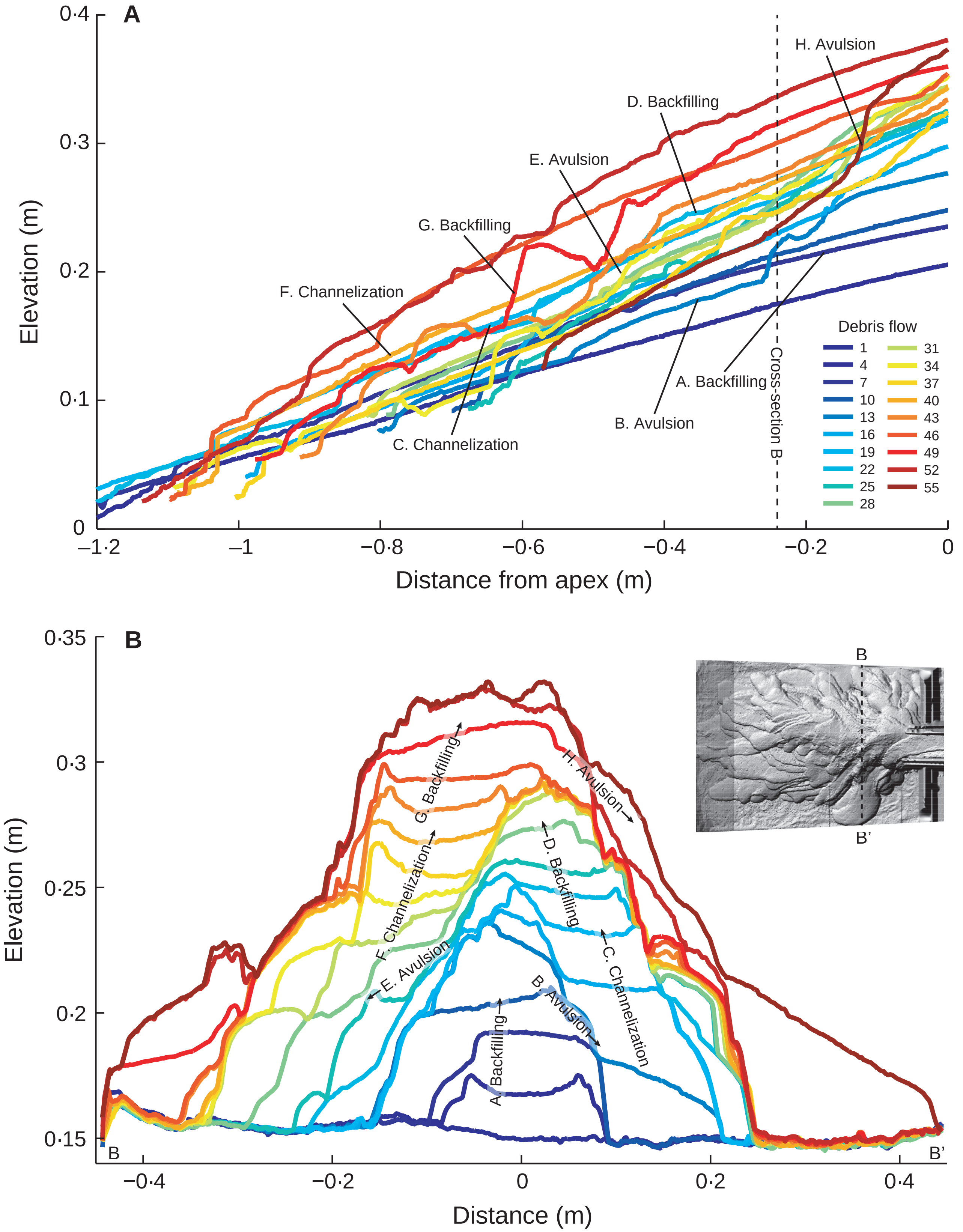

Fig. 6. Fan long-profiles and cross-profiles. (A) Long-profiles along the active debris-flow path. (B) Fan cross-profiles 0·23 m downstream of the fan apex.

Deposit thickness was highly variable due to interactions with antecedent topography and therefore hard to quantify by one value per debris flow. However, maximum deposit thicknesses were in the order of 1 to 2 cm for most debris flows (see Movie S8; Figs 8 and 9). Mean deposit thickness did not vary much between different phases of the autogenic cycle; only the location of lobe deposition varied. On average, lobe deposit thickness was similar or slightly higher than the thickness of levée deposits, which in general equals channel depth in the present experiments (Fig. 5). Flow depths were not measured in these experiments, but De Haas *et al.* (2015a) report flow depths for debris flows of similar volume, composition and feeder channel and outflow plain slope to range between 1·5 cm and 2.0 cm. Associated lobe and levée thicknesses in these experimental debris flows were in the same range as flow depth (and thus also similar to those observed on the debris-flow fan), suggesting that flow depths of the debris flows forming the fan were in the same range as those of De Haas *et al.* (2015a). Fan topography and roughness are thus a function of the debris-flow characteristics, being approximately of the same magnitude as the flow depth on the experimental fan.

Processes causing channelization, backfilling and avulsion sequences

The previous section shows that the experimental debris-flow fan formed by autogenic cycles of channelization, backfilling and avulsion. Below, the processes driving these cycles are detailed,

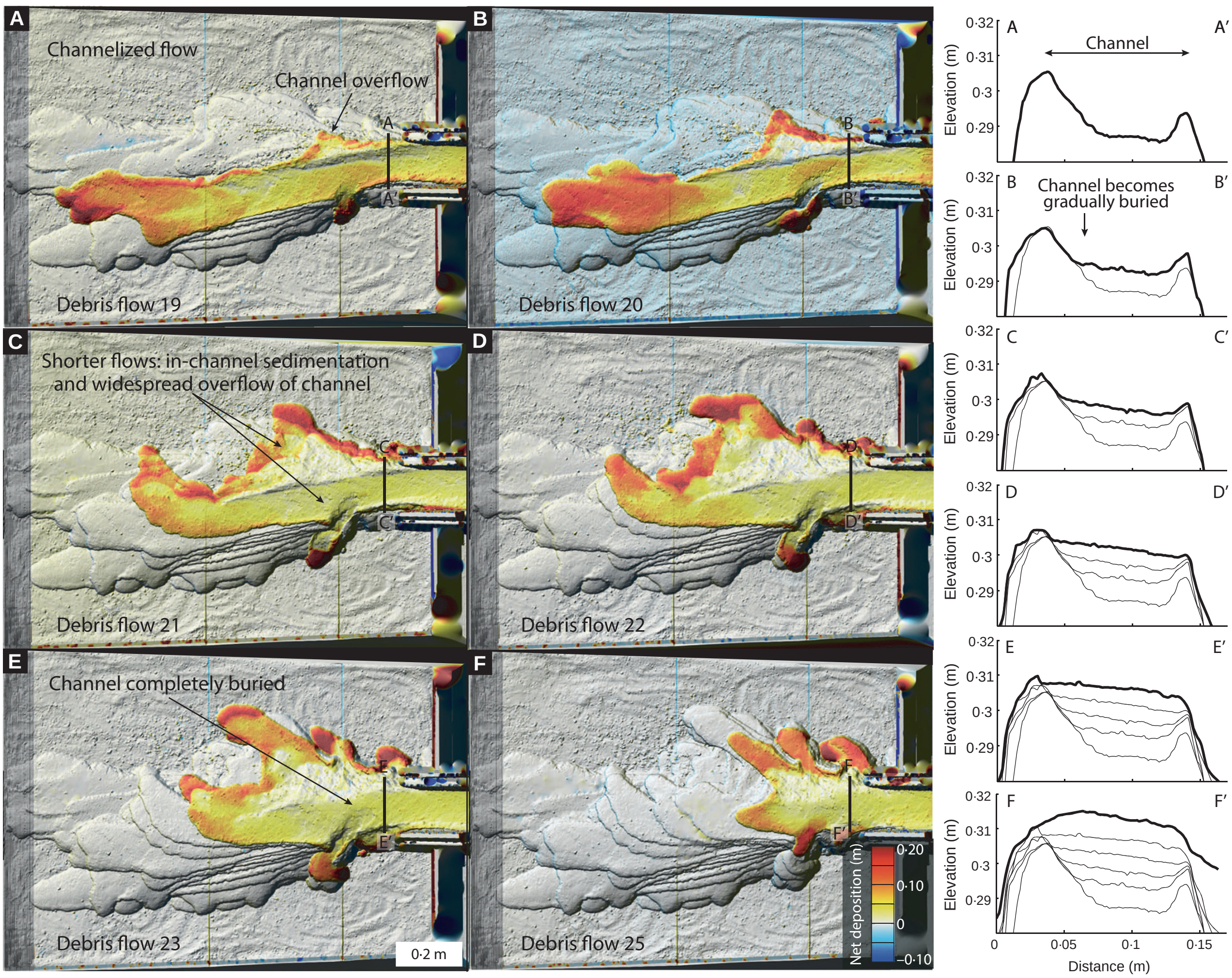

Fig. 7. Net deposition and channel cross-sections during progressive backfilling. (A) Debris flow 19. (B) Debris flow 20. (C) Debris flow 21. (D) Debris flow 22. (E) Debris flow 23. (F) Debris flow 25. See also Movie S8.

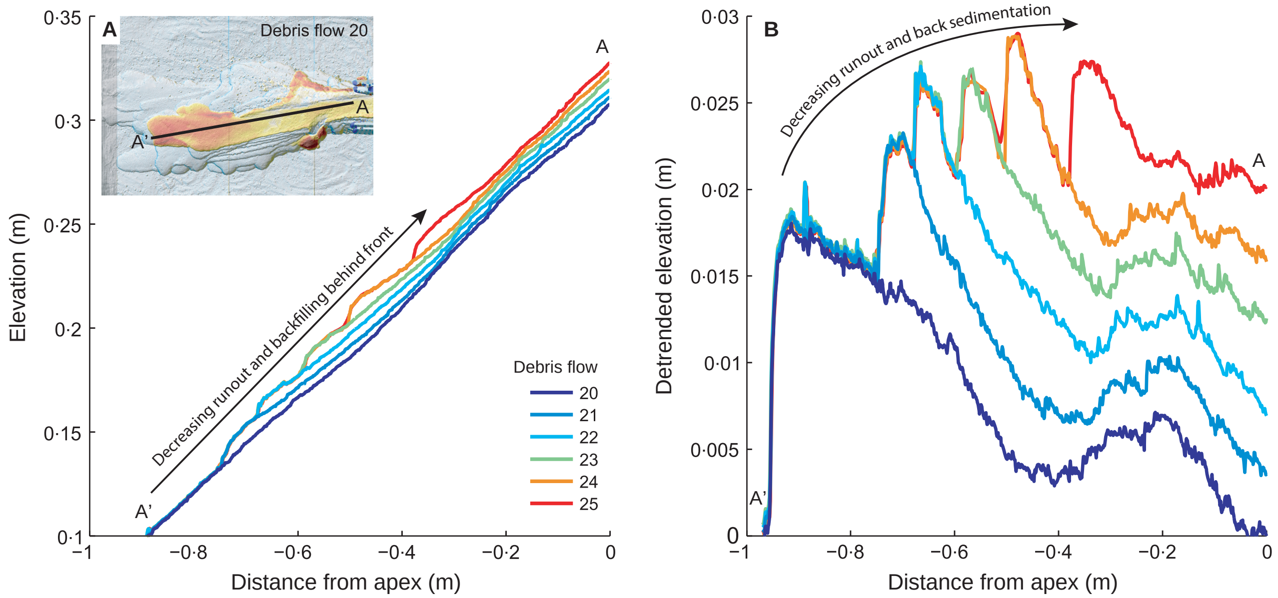

Fig. 8. Fan long-profiles from debris flows 20 to 25, illustrating the backfilling process. (A) Elevation profiles. (B) Detrended elevation profiles (by removing a linear fit). Debris-flow runout decreased progressively. Sedimentation behind the debris-flow snout caused in-channel sedimentation until the channel was completely filled (debris flow 25) and avulsion commenced (see Fig. 7B to F for channel cross-sections).

by analyzing debris flows 19 to 33 in detail (Figs 7 to 9). Starting from debris flow 16, a cycle of backfilling was initiated (Fig. 5). Debris flow 19 was still channelized (Fig. 7A) and accordingly most of its debris was deposited in its depositional lobe on the distal domain of the fan. However, slightly downstream of the fan apex a small amount of debris overflowed the channel. Overflow occurred at this location despite the presence of a relatively high levée, which suggests that overflow at this location was caused by the inertia of the debris flow. The next debris flow was slightly shorter but still channelized (Figs 7B and 8). Overflow occurred at the same location, but was more extensive. Because each debris flow had equal volume, the decrease in runout length of debris flow 20 relative to debris flow 19 led to more in-channel sedimentation, which decreased channel depth. The next debris flow then became shorter again, which caused increasing in-channel sedimentation, a decreasing channel depth and more extensive overflow (Fig. 7C). This feedback continued until debris flow 25 (Figs 7D to F and 8), after which the channel was completely buried, leading to a plano-convex cross-profile in the apex region (Fig. 7F).

Following the complete filling of the channel, subsequent debris flows gradually avulsed towards steeper fan gradients (Fig. 9A). Initially, the debris flows were relatively wide and short, and deposition was concentrated in multiple depositional lobes (Fig. 9A and B). However, the debris flows became increasingly long and narrow, as flows were progressively funnelled over the preferential flow path, until they became fully channelized (Fig. 9C to F). Channelization mainly resulted from the formation of lateral levées. From debris flows 30 to 33, these levées were stacked on top of one another, eventually leading to a well-developed and relatively deep channel (Fig. 5D). Interestingly, erosion was extremely limited and took place only in very localized areas with a high downstream gradient (Fig. 9D and E). This shows that the fan was fully aggradational and the channelization process was independent of incision.

The debris flows were observed to become progressively shorter or progressively longer because of a topographic compensation mechanism and feedbacks with flow momentum. The low-gradient slopes formed by end lobes forced subsequent debris flows to deposit further upstream. This effect is obvious from Figs 7 and 8 where debris flows shortened in several steps before avulsion commenced. Clearly, the terminal lobe of the debris flows acted as a barrier for the next debris flow, and shortened the debris-

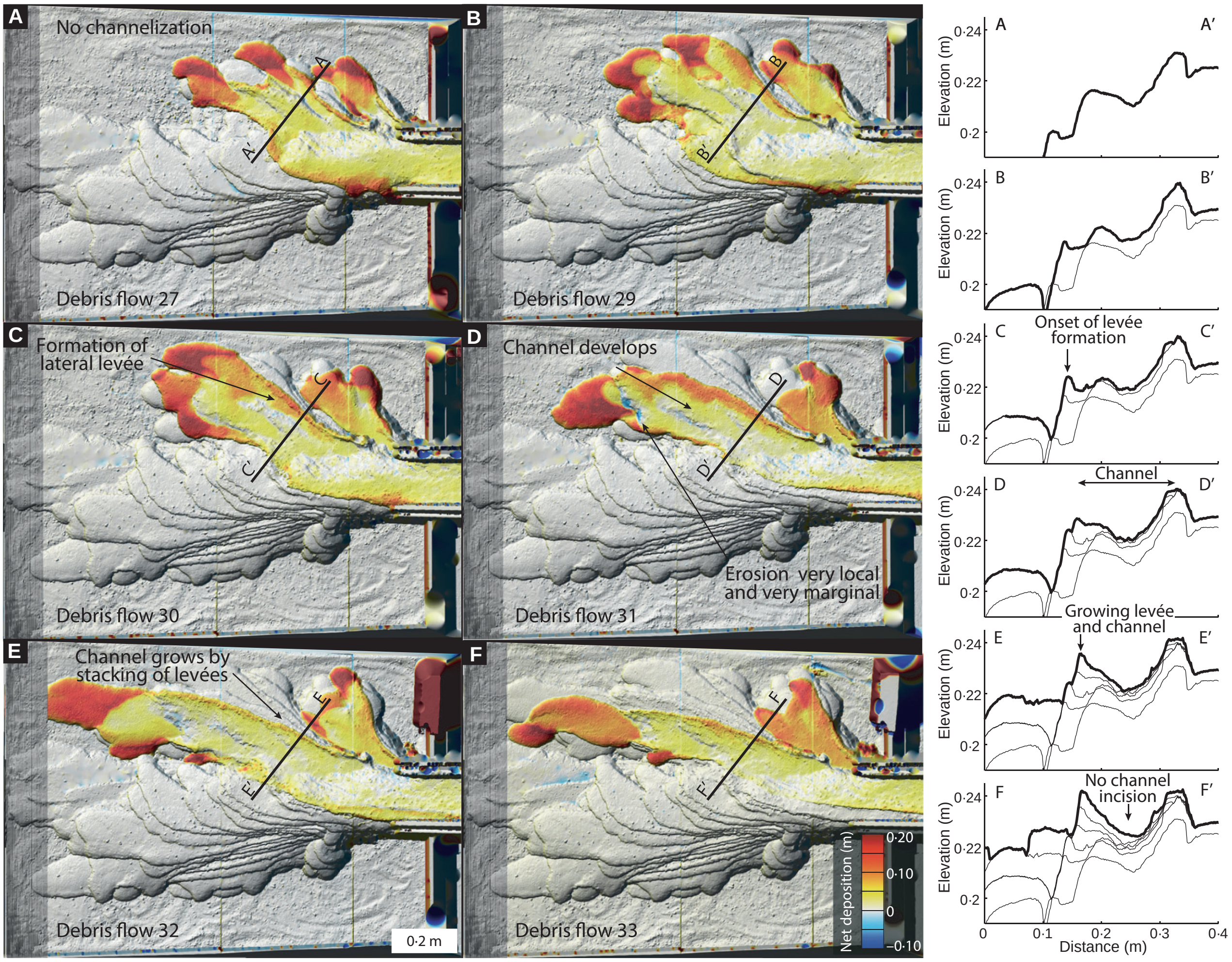

Fig. 9. Net deposition and channel cross-sections during progressive channelization. (A) Debris flow 27. (B) Debris flow 29. (C) Debris flow 30. (D) Debris flow 31. (E) Debris flow 32. (F) Debris flow 33. See also Movie S8.

flow channel. At the same time, the debris flows were observed to become progressively shorter due to a progressive decrease in flow momentum. The debris flows segregated into a coarse-grained flow front and finer-grained, more dilute, tail (Movies S10 and S11). At the coarse-grained flow front, flow resistance was higher and velocity was lower than in the more dilute material behind the flow front (i.e. the flow body). Consequently, the debris flows remained mobile as long as the momentum of the flow body exceeded the resistance at the flow front, whereas deposition commenced when the momentum of the flow body was insufficient to overcome the frontal friction. In a channelized state, debris-flow width was restricted, and consequently the momentum of the flow body was concentrated over a restricted width (Fig. 10A to C; Movie S10), which led to the formation of elongated debris flows and effective levée formation. However, channel infilling led to more overflow and a less focused momentum, which reduced runout together with the upstream migrated end lobe. This eventually led to very short and wide flows and a completely buried channel (Fig. 10D to F; Movie S11).

The effect of focusing of momentum was most obvious in the initial avulsion stages. Here, the first debris flows following avulsion were short and wide. On the most preferential flow path, outflow was greatest, whereas outflow over the other, less efficient, paths was less. Consequently, the latter paths became plugged and the relative gradient advantage over these paths became progressively smaller (Fig. 9A to D). Subsequent debris flows were therefore more effectively directed towards a single, most preferential, path. As a result, flow

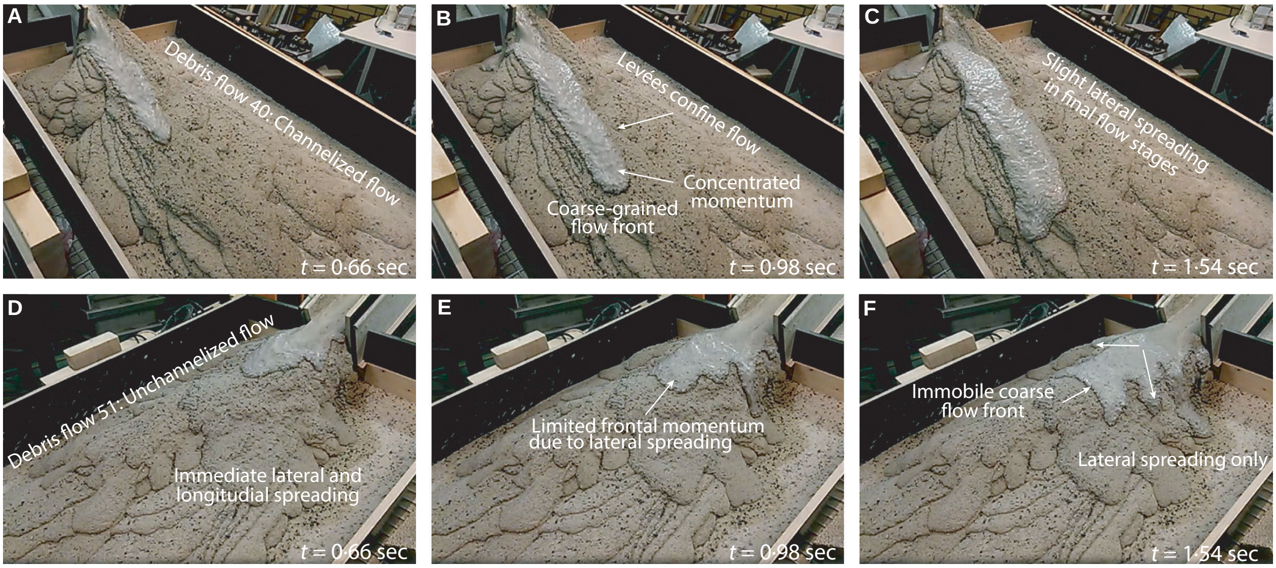

Fig. 10. Stills of debris flows during motion. (A to C) Channelized debris flow (debris-flow 40, Movie S10). (D to F) Unchannelized debris flow (debris-flow 51, Movie S11). Time (*t*) denotes time since the debris flow left the apex and outflow over the fan started.

momentum was more effectively focused to the flow front here, which led to larger runout and more effective levée formation. This, in turn, is a positive feedback mechanism leading to increasing runout length and better-defined channels until the debris flows reached their maximum possible extent given gradient, volume and composition, and a phase of backfilling was again initiated.

On the other hand, the effect of antecedent topographic steering by end lobes is most obvious in the backfilling stage. Here, a debris flow that was shorter than its predecessor caused more in-channel sedimentation and upstream migration of the main depositional lobe (Figs 7 and 8). The depositional lobe forced more upstream deposition because it provided a local low-gradient area (Fig. 8). This process continued until the debris flow channel was entirely filled and debris-flow material started to spill out of the channel. The spill meant a further reduction of momentum, which sped up the process of backfilling and the transition to avulsion (Fig. 10).

DISCUSSION

The present experimental debris-flow fan was formed by autocyclic sequences of avulsion, channelization, and backfilling. Channelization following avulsion appears to be the result of increasing focus of momentum and self-forming levées. On the other hand, backfilling appears to be the result of topographic steering and length reduction by prominent end lobes together with decreasing focus of momentum. These observations imply that observed changes in debris-flow fan morphology and flow conditions cannot automatically be attributed to extrinsic forcings (i.e. changes in catchment characteristics, tectonics, climate and base level). Moreover, they add debris-flow fans to the spectrum of subaerial fan-shaped fluvial systems that form by autogenic avulsion cycles, now ranging from subaqueous turbidite fans to subaerial low-gradient river systems and steep-gradient mass-flow fans (e.g. Ashworth *et al.*, 2007; Stouthamer & Berendsen, 2007; Hoyal & Sheets, 2009; Clarke *et al.*, 2010; Cantelli *et al.*, 2011; Straub & Pyles, 2012; Van Dijk *et al.*, 2012; Ventra & Nichols, 2014; Hamilton *et al.*, 2015).

Below, a conceptual model of autogenic dynamics on debris-flow fans based on the above described experimental fan is presented. Next, the experimental debris-flow fan is compared to previously reported experimental mass-flow fans of Hooke (1967) and Schumm *et al.* (1987) and to natural debris-flow fans. Then, the autogenic dynamics of experimental debris-flow

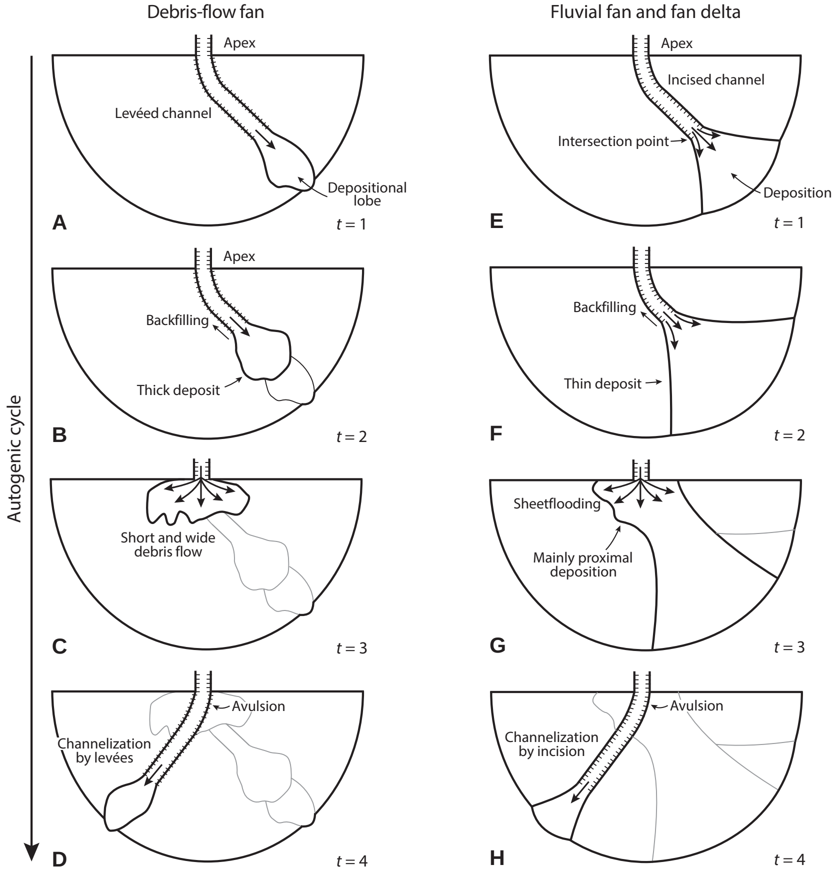

Fig. 11. Schematic portrayal of an autogenic cycle on experimental debris-flow fans and fluvial fans and fan deltas. (A to D) Autogenic cycle on the experimental debris-flow fan. Initially, the presence of a levéed channel results in distal deposition. Debris flows start to retrograde over many successive debris flows until the debris flows become short and wide and the channel is completely backfilled. In the absence of a channel, subsequent debris flows start preferentially flowing towards the steepest slopes and avulsion occurs. Debris flows now gradually, over the course of multiple successive flows, start channelizing and increase in length until a next cycle of retrogradation and backfilling commences. (E to H) Autogenic cycle on experimental fluvial fans and fan deltas, based on Van Dijk *et al.* (2012). Initially, apex incision results in deposition near the fan toe. Then the channel starts backfilling and the intersection point moves upfan. Once the channel is completely filled, sheetflooding results in proximal deposition, leading to oversteepening of the apex region until an inherent stability threshold is exceeded. This initiates avulsion by the formation of a new channel by erosion in the direction of the topographically lower areas of the fan. Sediment deposition is now concentrated distally again, until the next backfilling cycle commences.

fans are compared to the autogenic dynamics on other types of experimental fans. Finally, topographic compensation is discussed as an emergent mechanism forcing autogenic dynamics on all known fan types.

A conceptual model of autogenic dynamics on debris-flow fans

Based on the experimental observations, a conceptual model for the fundamental autogenic dynamics of debris-flow fans is developed (Fig. 11). Note that this model describes debris-flow fan dynamics in its most fundamental form, namely under fully constant extrinsic forcings, i.e. constant topography and debris-flow composition, rheology and volume. Overall, each autogenic cycle in debris-flow fan formation involves a sequence of: (1) backfilling; (2) avulsion; and (3) channelization.

Phase 1 involves backfilling of the debris-flow channel (Fig. 11B). Backfilling commences after the debris flows reach their maximum possible length (Fig. 11A). The next debris flow then becomes progressively shorter. The decrease in debris-flow length leads to more in-channel sedimentation and an upstream migrating depositional lobe. A shallower channel depth causes more overflow, which leads to a decrease of momentum of the liquefied flow body to the flow front. This decrease of momentum then reduces the velocity and runout length of the next debris flow, after which the process repeats itself. Simultaneously, the upstream migrating depositional front forces more upstream deposition of subsequent debris flows. Channel backfilling by debris flows is a gradual process, requiring multiple debris-flow episodes. It continues until the debris flows are very wide and short, the channel is completely filled, and the apex cross-profile is plano-convex (Fig. 11C).

Phase 2, avulsion, commences when the apex cross-profile is plano-convex. Here, there is no preferential transport direction by channelization. Debris flows initially spread laterally in both directions, but are progressively (over the course of multiple debris flows) directed towards the most preferential flow path. Simultaneously, the debris flows start to channelize.

Phase 3, channelization, is driven by the same processes as backfilling, only working in an opposite direction (Fig. 11D). The first debris flows after avulsion remain short and wide, but runout is greatest on the most preferential flow path. Consequently, less preferential paths become plugged. The next debris flow then more effectively follows the preferential path and, as a result, flow momentum is more focused, which leads to larger runout and more effective levée formation. This commences a feedback mechanism leading to increasing runout length and better-defined channels until the debris flows reach their maximum possible extent and the cycle is repeated.

Comparison to previous experimental mass-flow fans

The above described autogenic cycles observed on the present experimental debris-flow fan are similar to the cycles observed on the experimental mudflow fans described by Hooke (1967) and Schumm *et al.* (1987). Although these fans were partly built by stream-flow events, and the mass flows varied greatly in magnitude, sediment concentration and rheology, common denominators of both fans were the cycles of gradual backfilling, avulsion and channelization. Similar to the present debris-flow fan, channels were often formed by self-formed lateral levées, which then guided future flows. However, while channelization occurred in the absence of erosion on the

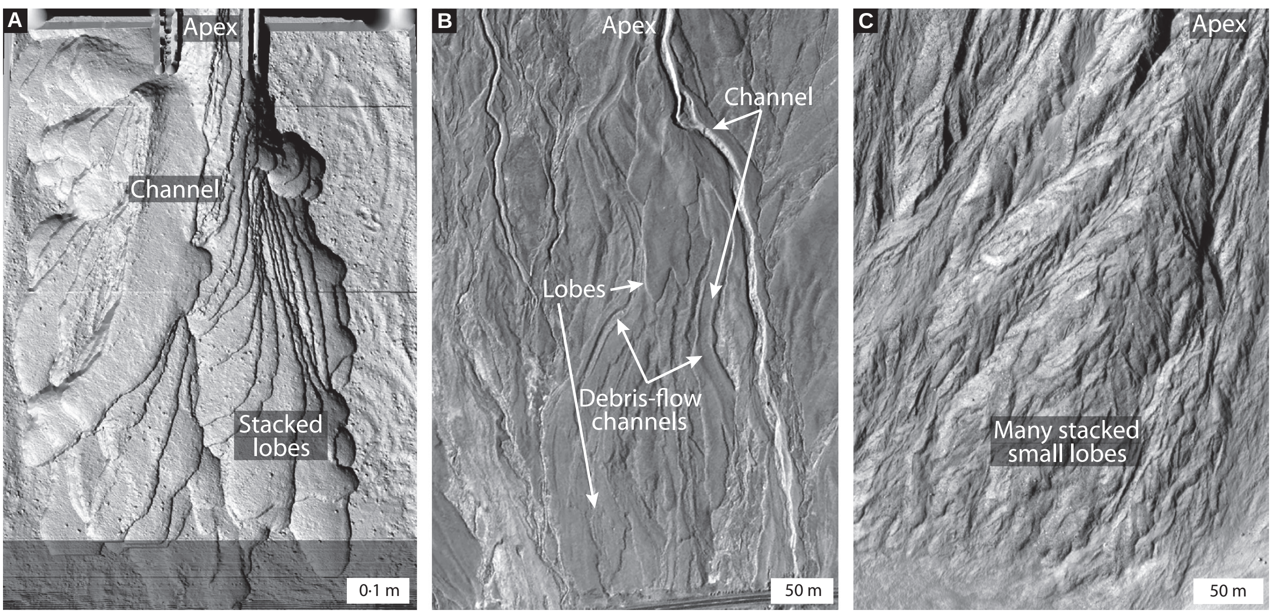

Fig. 12. Morphological comparison between the experimental and natural debris-flow fans from Earth and Mars. (A) Experimental debris-flow fan. (B) Debris-flow fan in the Atacama Desert in Chile (source: Google Earth). (C) Debris-flow fan on Mars (source: HiRISE image PSP_006837_1345) (Johnsson *et al.*, 2014; De Haas *et al.*, 2015b). Common denominators are the levéed channels and multiple stacked depositional lobes.

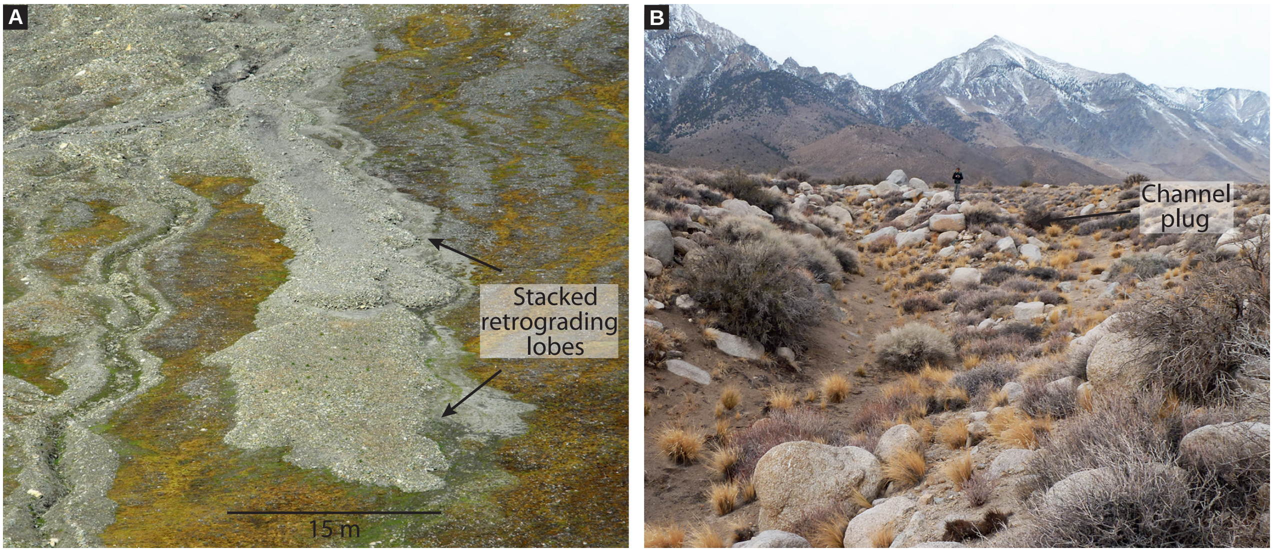

Fig. 13. Stacked retrograding debris-flow lobes and channel plugging on debris-flow fans. (A) Retrograded debris-flow lobes on a fan in Hanaskogdalen (Svalbard) (image credit: Ernst Hauber). (B) Debris-flow snout acting as a channel plug on Pinyon Creek Fan, Owens Valley, USA. Debris-flow snouts cause channel backfilling resulting in avulsion over the course of multiple debris flows on this fan, as described by Whipple & Dunne (1992).

present experimental fan, erosion contributed to channelization on the mudflow fans described by Hooke (1967) and Schumm *et al.* (1987). Both on the present debris-flow fan and on the mudflow fan of Schumm *et al.* (1987), flow velocity was lower in unchannelled flows that deposited in the apex region. Moreover, Schumm *et al.* (1987) observed that the filling and obliteration of the channels near the fan head permitted subsequent flows to avulse down the steeper slopes to the topographically lower parts, which is an avulsion mechanism similar to the mechanism observed on the present experimental debris-flow fan. However, both Hooke (1967) and Schumm *et al.* (1987) observed channel plugging events that forced successive flows to avulse, similar to observations from natural debris-flow fans (see below). This can probably be attributed to the varying composition, rheology and volume of the flows that build these experimental fans.

Comparison to the dynamics of natural debris-flow fans

The experimental debris-flow fan exhibited many of the morphological and textural features of natural debris-flow fans, including channels with lateral levées, and distinct, stacked, depositional lobes (Figs 12 and 13). Below the experimental cycles of autogenic gradual backfilling, avulsion and channelization are compared to the avulsive cycle observed on natural debris-flow fans. Note that on the natural fans, it is unknown whether these cycles are driven by autogenic or allogenic forcings. Additionally, the dynamics on natural fans are more complicated than on the present experimental fan for a number of reasons, including flows of various magnitude, composition and rheology and the effects of runoff (e.g. Whipple & Dunne, 1992).

There have been few direct field observations capturing the dynamics of debris-flow fans over the course of multiple debris flows. Examples are the Kamikamihori fan in Japan (e.g. Suwa *et al.*, 2011) and a small telescopic fan at Chalk Creek (USA) (Scheinert *et al.*, 2012; Wasklewicz & Scheinert, 2016). At the Kamikamihori fan, the spatial patterns of debris-flow deposition have been monitored for more than 40 years, in which 88 debris flows occurred. Multiple avulsions have been observed on this fan. Debris flows generally deposited over a narrow belt, associated with the active channel, during a period of several years. Within this belt, the terminal depositional points of successive debris flows progressively migrated upstream, after which avulsion occurred once the termination point reached the end of the fanhead (e.g. Suwa & Okuda, 1983; Okuda & Suwa, 1984; Suwa & Yamakoshi, 1999; Suwa *et al.*, 2011). On the small telescopic fan at Chalk Creek, elevation changes after five debris flows showed a gradual shift in the locus of deposition from the southern to northern part of the fan. The shift was initiated after a relatively large debris flow overtopped low-relief levées. Dühnforth *et al.* (2007) showed that Shepherd Creek fan (Owens Valley, USA) has evolved by alternating phases of backfilling leading to active channel backstepping followed by avulsion and fanhead incision.

Dendrochronology and lichenometry have been applied to reconstruct the spatio-temporal patterns of debris-flow deposition on multiple debris-flow fans (e.g. Blijenberg, 1998; Stoffel *et al.*, 2008). On four fans in the Bachelard Valley in the French Alps, Blijenberg (1998) found that the locus of debris-flow deposition generally gradually shifted from one side of the fan towards the other. However, there were a few exceptions where the locus of deposition shifted abruptly to the other side of the fan. Avulsion was also found to occur gradually (i.e. a relatively small angle difference relative to the apex between the locus of deposition of subsequent debris flows) or abruptly (i.e. a relatively large angle difference relative to the apex between the locus of deposition of subsequent debris flows) on forested debris-flow fans in the Swiss Alps (e.g. Bollschweiler *et al.*, 2007 2008; Stoffel *et al.*, 2008).

The above described avulsive dynamics are largely similar to those observed on the present experimental fan. On both the experimental fan and the Kamikamihori fan, avulsion took place after backfilling of the active channel. The avulsion process on the Chalk Creek fan and the fans in the Bachelard Valley generally was gradual, similar to the experimental fans. However, on natural debris-flow fans, there are notable exceptions at which avulsions happen more abruptly. On natural debris-flow fans, relatively small sediment volumes deposited in critical places along the channel, generally in the form of debris-flow snouts of relatively immobile debris flows or large boulders, (a process known as channel plugging) can force subsequent flows or flow surges in new directions (Fig. 13B; e.g. Beaty, 1963; Suwa & Okuda, 1983; Blair & McPherson, 1998; Schürch *et al.*, 2011a). This process can cause successive flows to avulse and lead to fundamental changes in the locus of sedimentation (Whipple, 1992; Dühnforth *et al.*, 2008), if the alternative flow path provides a more efficient pathway along the fan. Avulsions prior to complete backfilling of the active channel can also arise from large-volume flows that overtop the channel (e.g. Bollschweiler *et al.*, 2007; Wasklewicz & Scheinert, 2016). These modes of avulsion observed on natural fans suggest that complete cycles of backfilling of the main channel to the apex, as observed in the experimental fan, are likely to be rare on natural debris-flow fans. This is supported by the common presence of abandoned debris-flow channels on inactive fan sectors (Fig. 12B; e.g. Whipple & Dunne, 1992; Blair & McPherson, 1994), implying that avulsion was not preceded by complete backfilling of the channel. Yet, avulsion by channel plugging will generally only influence avulsion on a local scale; avulsion will only lead to large-scale shifts in the active locus if it occurs near the fan apex, because new flows can only follow a downward path. Moreover, if a debris flow is forced from the main channel in the apex region, it will only change its course substantially when there is a significant gradient advantage. A gradient advantage will, however, only be present when the old locus is topographically higher, which happens only when it has been the active locus for a considerable amount of time.

Natural debris flow fans are also often influenced by incision and sediment transport driven by run-off, which can greatly influence the fan surface morphology (e.g. Blair & McPherson, 2009; De Haas *et al.*, 2014). In general, run-off is concentrated in existing channels on the fan surface, which thereby generally are eroded and deepened. A deeper channel requires more debris flows to backfill and overtop the channel and avulsion to occur. Accordingly, Schumm *et al.* (1987) found that on an experimental mixed-flow fan, formed by alternating mudflow and stream-flow events, the stream-flow activity formed and enlarged fanhead trenches, reworked and partially sorted the mudflow deposits, and created conditions favourable for distal deposition of debris as the mudflows were effectively funnelled towards the distal domains of the fan. The present experimental debris-flow fan channelized in the absence of erosion. Nevertheless, natural debris flows are also observed to substantially erode channel beds (e.g. Suwa & Okuda, 1983; Berger *et al.*, 2011; Schürch *et al.*, 2011b; McCoy *et al.*, 2012). The processes governing debris-flow erosion are poorly understood (e.g. Hungr *et al.*, 2005; Schürch *et al.*, 2011b; Iverson & Ouyang, 2015) and, consequently, it is largely unknown which debris-flow types cause erosion and which do not.

Comparison of autogenic dynamics of debris-flow fans and other fan types

The generic characteristics of the autogenic cycle of the present experimental debris-flow fan are similar to the generic characteristics of the autogenic cycle on experimental fluvial fans and deltas and turbidite fans (e.g. Schumm *et al.*, 1987; Clarke *et al.*, 2010; Cantelli *et al.*, 2011; Hamilton *et al.*, 2015; Fig. 11).

In general, the dynamics on experimental fluvial fans and fan deltas and turbidite fans are as follows (Fig. 11E to H). Autogenic fan construction is governed by quasi-cyclic alternation of unconfined and channelized flow (e.g. Schumm *et al.*, 1987; Bryant *et al.*, 1995; Whipple *et al.*, 1998; Davies & Korup, 2007; Kim & Muto, 2007; Kim & Jerolmack, 2008; Van Dijk *et al.*, 2009 2012; Clarke *et al.*, 2010; Reitz *et al.*, 2010; Powell *et al.*, 2012). Phases of unconfined flow induce aggradation on most of the alluvial fan until a critical threshold slope is reached; this results in a phase of fanhead incision creating progressively expanding channelized flow. The incision focuses sediment transport and fan progradation distally along limited radial sectors, where deposition is forced by a mouth bar which reduces the gradient and stream power. When deposition reduces the gradient below a critical value, a phase of progressive backfilling is induced, characterized by initial aggradation within the incised channel, until flow expands out of the channel and forces widespread aggradation progressively upstream induced by an upstream migrating mouth bar. This progressive backfilling then continues until the channel is largely backfilled and the slope becomes critically high, and avulsion and another phase of fanhead incision is initiated.

Avulsion cycles on experimental fluvial and debris-flow fans are thus governed by alternations of backfilling, avulsion and channelization. The main differences between the fan types are in the processes that drive these alternations. On experimental fluvial fans and deltas and turbidite fans, the autogenic cycles are mainly governed by constraints on morphology and critical slopes. In contrast, on the present experimental debris-flow fans, these cycles were mainly governed by feedbacks of morphology and debris-flow flow-dynamics. Most fluvial fans operate more continuously in time, changes in the surface morphology take place more gradually, and the sediment flux and maximum transportable grain size are typically limited by the flow velocity and available stream power (Schürch, 2011). Channel morphology (characterized principally by depth, width:depth ratios, sinuosity and degree of internal aggradation) has been shown to be an important control on the frequency, location and direction of avulsion on fluvial fans (Schumm *et al.*, 1987; Field, 2001). In contrast, debris flows are events with a finite duration and spatial extent, i.e. deposition by debris flow is highly localized (Schürch *et al.*, 2011a). As such, they deposit sediment very locally in relatively thick deposits in contrast to fluvial flows which deposit their sediment generally over larger areas and in much thinner deposits (e.g. Blair & McPherson, 2009; Fig. 11). For this reason, debris-flow fans generally have rougher surfaces than fans dominated by fluvial flows (e.g. Volker *et al.*, 2007; Wasklewicz *et al.*, 2008).

On experimental fluvial fans and deltas and turbidite fans, phases of backfilling are initiated when the active channel drops below a critical slope (e.g. Schumm *et al.*, 1987; Clarke *et al.*, 2010; Reitz *et al.*, 2010; Van Dijk *et al.*, 2012; Hamilton *et al.*, 2015). On the experimental debris-flow fan phases of backfilling appear to initiate after the debris flows have reached their maximum possible runout distance. Debris-flow fan slope is a function of the runout distance of the debris flows forming the fan (Jackson *et al.*, 1987; Marchi & Tecca, 1995; Chau *et al.*, 2000), suggesting similar topographic controls on the formation of debris-flow fans and fluvial fans, and deltas and turbidite fans. Backfilling appears to be driven by an upstream migrating mouth bar for fluvial fans and deltas and turbidite fans (e.g. Van Dijk *et al.*, 2012) or depositional lobe for debris-flow fans. Channel backfilling is a prerequisite for avulsion on all fan types, because the channel has to be filled and the active sector on which the channel is present has to become elevated above its surroundings (Postma, 2014). Due to the finite spatial extent of debris flows, backfilling for these flow types is governed mainly by retrograding shingled stacking of debris flows (i.e. every subsequent debris flow is slightly shorter). On the experimental fluvial fans and deltas and turbidite fans, the intersection point (the point where the channel ends on a fan) progressively moves upfan. Below the intersection point the flow spreads laterally, stream power declines and sediment is deposited (e.g. Clarke *et al.*, 2010; Van Dijk *et al.*, 2012; Hamilton *et al.*, 2015). On fluvial fans, backfilling of the channel eventually results in spatially wide sheet flows in the apex region (e.g. Schumm *et al.*, 1987; Whipple *et al.*, 1998). This depositional pattern corresponds well with the short and wide debris flows that occur on the present experimental debris-flow fan at the end of a backfilling phase. On both fan types, backfilling is a gradual process.

On experimental fluvial fans and deltas, the avulsion trigger is related to steepening of the fan apex by unconfined sheet flows. Once a critical slope is exceeded, incision commences at the fanhead, forming a channel and inducing the channelization phase. This incision then progressively focuses sediment transport and progradation distally along limited radial sectors. Similarly, on experimental turbidite fans, new channels following avulsion are also formed by incision (Hamilton *et al.*, 2015). In contrast, on the present experimental debris-flow fan channelization was induced in the absence of erosion by the formation of lateral levées.

The autogenic cycles on the present experimental debris-flow fan were symmetrical: i.e. the number of debris flows in the backfilling and channelization phase was approximately equal. In contrast, on the experimental fluvial fans described by Van Dijk *et al.* (2009) and Van Dijk *et al.* (2012), the channelization phase was much shorter than the backfilling phase. This dissimilarity probably results from the erosive nature of the channelization process on fluvial fans, which probably makes channelization a more efficient and therefore more rapid process than on the present experimental debris-flow fan, where channelization occurred in the absence of erosion.

An emergent mechanism of autogenic fan dynamics: topographic compensation

As discussed above, autocyclic dynamics have been identified on a wide range of fans, despite very different formative mechanisms ranging from subaerial rivers, sheet flows and debris flows to subaqueous turbidity currents (Stouthamer & Berendsen, 2007; Cantelli *et al.*, 2011; Van Dijk *et al.*, 2012; Ventra & Nichols, 2014). This suggests the presence of an emergent mechanism that governs the autocyclic dynamics on different types of fan-shaped landforms.

All flow mechanisms known to form fans are driven by gravity. This inevitably results in flow routing preferentially following the steepest slopes over a fan surface, which results in deposition and aggradation in topographic lows between older deposits. This process of topographic compensation leads to spatially uniform aggradation rates on fans over long timescales. Compensational stacking occurs over various spatial and temporal scales, ranging from subsequent individual depositional events that aggrade directly adjacent to one another over very short timescales of hours to years to complete shifts of active fan sectors that generally require hundreds to tens of thousands of years.

All fan types exhibit cyclic alternations between channelized–unchannelized and prograding–retrograding phases, regardless of the formative mechanics of the channel (i.e. incision or levée formation; e.g. Schumm *et al.*, 1987; Cantelli *et al.*, 2011; Van Dijk *et al.*, 2012). On a channelized fan, flows are directed towards a predefined area bounded by topography where deposition can occur. As such, deposition and aggradation can only occur in 'local' lows within this predefined area. Deposition in the 'absolute' low on the fan surface can only occur after major avulsion of the active sector, which only happens when the channel has been filled and the active sector is superelevated above the surrounding fan surface. Channelization thus results in a temporal and spatial delay of compensational stacking, and generally results in a stepwise rather than smooth lateral migration pattern. In synthesis, the similarity of the pattern of fan formation over sufficiently large spatial and temporal scales, suggests that the formative dynamics of fan-shaped landforms, regardless of their formative mechanisms, can be reduced to the process of topographical compensation over large spatio-temporal scales.

CONCLUSIONS

Debris-flow fans were experimentally created under constant boundary conditions to investigate their autogenic dynamics. The resulting fan was morphologically similar to natural debris-flow fans, in that it consisted of stacked lobes and channels bordered by lateral levées. Two autogenic cycles of backfilling, avulsion and channelization occurred on the fan. The backfilling and channelization phases required a similar number of successive debris flows.

Backfilling commenced after debris flows reached their maximum possible length, given by the initial slope and debris-flow volume and composition. An upstream migrating depositional end lobe together with a decreasing focus of flow momentum caused progressively shorter debris flows. Ultimately, the channel was filled and flows became wide and short resulting in a plano-convex apex region. This resulted in avulsion towards the preferential flow direction, given by the balance between steepest descent and flow inertia. Following avulsion, outflow was greatest on the preferential flow path while other paths were plugged. Thus, momentum became increasingly focused, leading to larger runout and more effective levée formation. This process continued until the debris flows reached their maximum possible extent, which is defined by topography and their composition and volume, and backfilling then recommenced.

Important characteristics of the experimental avulsion cycles have also been observed on natural debris-flow fans, although natural debris-flow fans were generally formed by individual debris flows that vary in magnitude, composition and rheology. Over large spatial and temporal scales, avulsion cycles appear to be governed by large-scale topographic compensation on debris-flow fans, similar to the processes driving avulsion cycles on fluvial fans and deltas and turbidite fans, although the detailed processes are unique for debris-flow fans. These results add debris-flow fans to the spectrum of fan-shaped depositional systems that exhibit autogenic dynamics, now ranging from subaqueous turbidite fans to subaerial low-gradient river systems and to steep-gradient mass-flow fans.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Movie S1. Movie of top-view pictures taken after each debris flow on fan 01.

Movie S2. Movie of top-view pictures taken after each debris flow on fan 02.

Movie S3. Movie of top-view pictures taken after each debris flow on fan 03.

Movie S4. Movie of top-view pictures taken after each debris flow on fan 04.

Movie S5. Movie of top-view pictures taken after each debris flow on fan 05.

Movie S6. Movie of hillshade images of the fan after each debris flow on fan 03.

Movie S7. Movie of digital elevation model (DEM) of the fan after each debris flow on fan 03.

Movie S8. Movie of net deposition after each debris flow on fan 03.

Movie S9. Movie of all debris flows during motion on fan 03.

Movie S10. Slow motion movie of a channelized debris flow (debris flow 40).

Movie S11. Slow motion movie of an unchannelized debris flow (debris flow 51).