Autogenic Controls on Debris-flow Fans with Limited Accommodation Space:

Laboratory Experiments informed by a Field Example

by

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Decades of historic levels of urbanization and expansion of the built environment on to existing alluvial fans at the periphery of most cities has placed humans at risk of floods and debris-flows that are formative processes on alluvial fans. Understanding the evolution of these features is to understand risks to human lives and infrastructure in these locations. Therefore, there is a need to explore the myriad of factors affecting alluvial fan evolution. Here, physical modeling is used to explore the effect of limited longitudinal accommodation space on autogenically derived debris-flow fan evolution.

Physical modeling has furthered our understanding of the formative processes of alluvial fans, in part, by allowing for the isolated control of any number of variables. Operating in a laboratory setting also allows researchers to overcome potential challenges posed by field work (site remoteness, hazardous environments, unpredictability of phenomena, etc.) while creating an environment for manageable data collection. Prior alluvial fan physical modeling has largely focused on fluvially generated fans rather than those dominated by debris flow deposition. Moreover, the studies that have considered the latter have only done so under the assumption of unlimited accommodation space (the area in which fans can prograde); an assumption that is frequently not representative of natural conditions.

Here, two debris-flow fans are generated using a small-scale physical model in order to explore the influence of limited longitudinal accommodation space on autogenic avulsion patterns. Fan-toe erosion is simulated through the repeated removal of debris-flow material at a fixed distance from the fan apex. Aided by high-resolution terrestrial laser scanning (TLS) data, geomorphic change detection and topographic profiles are used to examine differences in fan evolution.

Results from small-scale physical modeling experiments show that cycles of channelization, the formation and persistence of a stabilized channel, channel narrowing and overflow, and avulsion result in the formation of new fan segments on a debris-flow fan with limited accommodation space. These results provide evidence for an explanation of debris-flow fan evolution alternative to the most widely accepted theory which can be summarized as cycles of channelization, backfilling, and avulsion. Furthermore, these results are informed and supported by field observations of a debris-flow fan located in Chalk Cliffs near Nathrop, Coloradao, USA where the fan-toe is periodically eroded by Chalk Creek.

AUTOGENIC CONTROLS ON DEBRIS-FLOW FANS WITH LIMITED ACCOMMODATION SPACE: LABORATORY EXPERIMENTS INFORMED BY A FIELD EXAMPLE

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CHAPTER 1: INTRODUCTION

Introduction

Decades of historic levels of urbanization and expansion of the built environment on to existing alluvial fans at the periphery of most cities has placed humans at risk of floods and debris-flows that are formative processes on alluvial fans (Cavalli and Marchi, 2008). Loss of human lives and destruction of human settlements by debris-flows is not a new occurrence. A precipitation induced debris-flow in 1998 claimed the lives of 2500 people in the villages of El Porvenir and Rolando Rodriguez, Nicaragua (Scott et al., 2000). One year later heavy rainfall from a storm near Caracas, Venezuala ended in the deaths of 210 people with thousands more injured and temporarily displaced (Wieczorek et al., 2001). The high losses in lives and property are often a result of the swift development of debris-flows. Debris-flows are often associated with high-intensity rainfall (Costa, 1984) that leads to rapid runoff and debris-flow initiation in the upper drainage basin leads to bulking of sediment along the feeder channel prior to debouching onto a debris-flow fan. Debris-flows may consist of approximately 10^3 m^3 (larger events exceeding 10^9 m^3) in volume and move at speeds of 1-13 m/s, frequently exhibiting a pulsing flow pattern as debris moves in multiple surges down the feeder channel (Iverson, 1997; Blair and McPherson, 2009). These characteristics along with the combination of solid and fluid physical forces that characterize debris-flows present a unique destructive power that may be propagated over long distances (potentially >= 1 km) (Iverson, 1997). The destructive nature of debris-flows present a need to resolve the components and interactions by which debris-flows modify and in turn are modified by the topography of debris-flow fans. The application of scientific results from these types of studies is of vital importance to hazard mitigation and adequate urban planning (Hurlimann et al., 2006).

Application of Physical Modeling in Alluvial Fan Literature

Early physical modeling experiments

A variety of processes are important to alluvial fan development, which include dominant depositional processes (fluvial-, mixed-, or debris-flow dominated fans), effects of allogenic and autogenic processes (processes generated outside of and within the fan system, respectively [Beerbower, 1964]), and limitations on accommodation space. The complex interactions of these factors and the difficulty of being onsite at the time of the event have led many researchers to turn to physical models. Physical models allow a researcher to work in a controlled setting where multiple formative events can be run in a short period of time and particular processes or variables can be isolated to examine landform dynamics (Clarke, 2015). Landforms in physical models often exist at scales that are readily measurable, which has made the experiments easy to record across the entire alluvial fan surface.

Physical modeling is not a novel approach, dating back to the early work of Hooke (Hooke, 1967; Hooke, 1968; Hooke and Rohrer, 1979) and Schumm (Schumm, 1977; Schumm et al., 1987). Conclusions from these early experiments formed a body of fundamental observations of fan form and processes. These authors demonstrated that many of the fundamental features and processes (i.e., avulsions, lateral migration, channel entrenchment, channelization, and sheetflow) present in natural alluvial fans are represented in small scale physical experiments. Findings from these experiments were compared to field evidence, but the experiments themselves are not directly representative of any specific natural feature. A *similarity of processes* approach is used to compare the physical model results to natural features based on the theory that morphodynamics active on the experimental and natural surfaces are scale independent (Paola et al., 2009). Identification of general processes such as cyclic channelization, incision, backfilling and avulsion (Schumm et al., 1987) and depositional cycles caused by local increases in elevation followed by depositional transition to topographically lower fan areas (Hooke and Rohrer, 1979) are important contributions from early physical modeling. Later physical experiments expanded on these fundamental findings and methods.

Physical modeling and allogenic processes on alluvial fans

Physical model investigations have included a wide variety of experiments aimed at isolating and quantifying specific aspects of process-form interactions on alluvial fans. Many studies have been conducted in pursuit of examining the relationship between external factors and fan morphology. Base level, tectonic, and climatic changes can alter input conditions, which greatly affect alluvial fan response. Guerit et al., (2014) found that fan geometry is controlled by water discharge by setting the fan slope near its critical value while sediment supply controls the rate at which the fan grows. Hooke and Dorn (1992) created a Froude-scale model, a model that is scaled to individual prototypes, to better understand entrenchment and segmentation on a set of alluvial fans located in Death Valley, California, concluding that incision and associated surface abandonment at these sites were directly related to a wetter climate. Experimental work dealing with alluvial fans and fan deltas has increased knowledge on how the formation of stratigraphy is associated with and determined by base level changes and variable sediment supply (Paola et al., 2001; Sheets et al., 2002; Martin et al., 2009). Whipple et al., (1998) investigated how alluvial fan slope responds to climatic and tectonic forcings. Experimental alluvial fans were created under constantly rising base level and variable water discharge, sediment supply, and median grain size. These authors found that fan slope held a strong, inverse relationship with water discharge as well as a strong, direct relationship with sediment supply. Median grain size reportedly has no influence on fan slope while bedload flow was high (Whipple et al., 1998).

Physical modeling and autogenic processes on alluvial fans

The influence of autogenic dynamics on alluvial fan surfaces has also been investigated in early physical modeling experiments. Flow conditions were observed to undergo changes because of internal interactions on the fan surface in the absence of external factor variability (Hooke, 1968; Hooke and Rohrer, 1979; Schumm et al., 1987). Analog physical modeling gave researchers the ability to manipulate external factors to produce fans governed solely by autogenic processes. These techniques have allowed researchers to identify the significance of the range of flow processes on alluvial fan evolution. Under constant allogenic forcings, experimental alluvial fans and fan deltas experienced cyclic channelized flow and sheetflow which heavily influenced locations of subsequent areas of deposition (Hoyal and Sheets, 2009; Clarke et al., 2010; van Dijk et al., 2008, 2009, 2012). These same flow processes have also been witnessed on experimental fans generally controlled by extrinsic factors and also influenced by autogenic processes (Kim and Paola, 2007; Kim and Jerolmack, 2008). The importance of flow conditions, specifically whether subritical or supercritical flow is dominant, has also been demonstrated through physical modeling. Tendency toward channel reoccupation following avulsion was revealed in the experimental fans of Reitz et al., (2010) and Reitz and Jerolmack (2012). Backfilled channels left an imprint on the fan surface that encouraged reoccupation and was associated with subcritical flow on these fans. This conclusion was drawn from Hamilton et al., (2013) as these authors noted that no apparent footprint remained after channels backfilled in supercritical flows.

Physical modeling and accommodation space dynamics on alluvial fans

A variable that has not received significant consideration in the physical modeling research is the role of accommodation space. This is at odds with the frequency of limited accommodation space surrounding alluvial fans in natural settings (Harvey, 1984; Calvalche et al., 1997; Viseras et al., 2003) (Figure 2.1). The presence of boundary conditions associated with accommodation space have been studied in physical models of alluvial fans and fan deltas (van Dijk et al., 2012; Clarke et al., 2010). Van Dijk et al., (2012) studied the effects of ponding water at the distal boundary of fan deltas on cycles of channelization and backfilling as compared to alluvial fans. They found that channelization and subsequent backfilling is much more pronounced and less prone to autogenic disturbance on fan deltas as compared to alluvial fans. Clarke et al., (2010) simulated fan-toe erosion for fluvially dominated alluvial fans and found that limited accommodation space, autogenic cycles of deposition (channelization and backfilling) ceased to exist. Instead, once channelization was initiated and the fan reached the downstream boundary, backfilling did not occur because the incised channels had progressed to a level that became fixed with the base level.

Basis for expanding knowledge surrounding autogenic debris-flow fan development

The majority of the research reviewed so far has focused on modeling fluvial-flow fans and fan deltas rather than debris-flow fans. Furthermore, research focusing on debris-flow fans have exclusively explored influences from allogenic processes rather than autogenic processes. De Haas et al. (2016), however, investigated the autogenic dynamics of debris-flow fans by creating debris-flow fans under constant extrinsic variables in a novel experiment. These experiments revealed variance in debris-flow morphology cannot be explicitly explained by allogenic factors. He observed phases of channelization and backfilling caused by self-formed, coarse-grained lateral levees; increasing and decreasing focus of momentum; and presence of prominent depositional end lobes. These cycles of channelization and backfilling lead to fan avulsion, proving that debris-flow fan evolution can result from intrinsic properties. This last finding bolsters field evidence of avulsion cycles occurring on much shorter time scales than what could be produced through changes in allogenic factors alone (Harvey et al., 1999; Allen, 2008; Stoffel et al., 2008; Wasklewicz and Scheinert, 2016).

De Haas' et al. (2016) findings align with the most widely accepted theory of alluvial fan evolution as observed on several physical modeling experiments (Schumm et al., 1987; Kim and Muto, 2007; Kim and Jerolmack, 2008; Van Dijk et al., 2009, 2012; Clarke et al., 2010; Reitz and Jerolmack, 2012; and Hamilton et al., 2013) as well as in field studies (e.g., Field, 2001; Ventra and Nichols, 2014). Evidence from these studies highlight an evolutionary pathway that exhibits seven phases of change that lead to alluvial fan development:

(1) periods of fan-wide aggradation associated with periods of sheetflow/unchannelized flow followd by;

(2) channelization of flow and channel incision/formation on the fan surface that leads to;

(3) fan progradation via the formation of depositional lobes until;

(4) the channel begins to backfill toward the fan apex;

(5) backfilling promotes avulsion as the channel can no longer contain flows;

(6) the creation of a new fan segment; and

(7) the process repeats itself.

While this cycle of (shortened for ease of use) channelization, backfilling, and avulsion is the most widely supported theory of alluvial fan evolution, an alternative explanation has been alluded to in the literature. Bryant et al., (1995) recognized a direct, positive relationship between avulsion frequency and sedimentation rates. These authors found that as sedimentation rates increase, the rate of avulsion increases at a “faster than linear” rate while overall fan slope increases; meaning that less sediment is needed to trigger avulsions as sedimentation rates increase. These findings are indicative of alluvial fan super elevation leading to a critical state near the fan apex whereby any number of processes could trigger avulsion by any number of mechanisms (Bryant et al., 1995). The authors posit that the general increase in overall fan slope is likely a contributing factor to the inverse relationship between sediment required to initiate an avulsion and sedimentation rates (Bryant et al., 1995). Hooke and Rohrer (1979) created experimental alluvial fans and found that deposition occurs on one area of the fan for an undetermined amount of time, and in doing so, creates a fan segment that is topographically higher than the surrounding surfaces. The relative increase in elevation eventually causes avulsion to occur along the interface between these ‘high’ and ‘low’ areas where fan gradient is greatest. A similar pattern has also been insinuated from TLS monitoring of a telescoping fan near Nathrop, Colorado (Wasklewicz and Scheinert, 2016).

Through a series of small-scale experiments, De Haas (2016) showed that cycles of avulsion, channelization, and backfilling are intrinsic processes on debris-flow fans as the experiments were conducted under constant allogenic forcing. These findings bolster field evidence of avulsion cycles occurring on much shorter time scales than what could be produced through changes in allogenic factors alone (Harvey et al., 1999; Allen, 2008; Stoffel et al., 2008; Wasklewicz and Scheinert, 2016). Since avulsion, and therefore changes in areas of potential hazard, on debris-flow fans can be produced through autogenic processes that take place on relatively short time scales, a need arises to understand these avulsion dynamics in the variety of natural environments in which debris-flow fans exist. This study is primarily concerned with the effects limited longitudinal accommodation space may have on autogenic avulsion cycles on debris-flow fans. Limited longitudinal accommodation space in this study is simulated to resemble fan-toe erosion by a trunk stream; such a scenario is shown in Figure 2.1 where an unnamed debris-flow fan located in Chalk Cliffs near Nathrop, Colorado is periodically eroded at the toe by Chalk Creek.

Since few studies consider the effects of autogenic dynamics on debris-flow fan avulsion cycles and fewer than that, if any, explicitly consider these scenarios under limited accommodation space and since a combination of these factors could potentially change the time-scale and location by which debris-flows occur and deposit, the following research question and hypothesis is proposed:

(Q1) Does limited alluvial fan longitudinal accommodation space change the autogenic processes responsible for the development of a new alluvial fan segment?

(H1) Frequent fan-toe removal on autogenically controlled debris-flow fans result in super elevation of the active fan segment which leads to shifts in the locus of deposition.

The experimental research will be focused solely on fans produced by debris-flows with consistent rheology as well as fan-toe erosion simulated by an unaltered channel. In reality, debris-flow rheology is variable and can greatly influence runout patterns and overall fan gradient (Staley et al., 2006; Major, 1997) and long-term depositional patterns (Whipple and Dunne, 1992). Streams adjacent to debris-flow fans are also rarely stable systems that are heavily influenced by debris-flow deposits. Wasklewicz and Scheinert (2016) note channel plugging and downstream bifurcation succeeding debris-flows. As a result, fan-toe erosion is temporally inconsistent and spatially variable. Factors such as these surpass the scope of this research. However, the information gained here will likely provide a basis for exploratory research with these variables in mind.

CHAPTER 2: LABORATORY EXPERIMENTS

Introduction

Debris-flow fans, formed through depositional sediment-gravity processes, are a sub-category of alluvial fans that occur in mountainous environments worldwide. These features evolve through cyclic avulsion cycles that continuously redefine active and inactive fan sectors (Blair and McPherson, 2009; Frankel and Dolan, 2007). De Haas et al. (2016), with the aid of physical modeling experiments, showed cycles of avulsion, channelization, and backfilling are intrinsic processes on debris-flow fans. These findings bolster field evidence of avulsion cycles occurring on time-scales shorter than those identified in allogenic factors alone (Harvey et al., 1999; Frankel and Dolan, 2007; Allen, 2008; Stoffel et al., 2008). Since avulsion, and therefore changes in the location and spatial extent of potential hazards, on debris-flow fans can be produced through autogenic processes that take place on relatively short time scales, a need arises to understand these avulsion dynamics in the variety of natural environments in which debris-flow fans exist. This study is primarily concerned with the effects limited longitudinal accommodation space may have on autogenic avulsion cycles on debris-flow fans. Limited longitudinal accommodation space in this study is simulated to resemble fan-toe erosion by a trunk stream. Here, the study is informed by field experience at an unnamed debris-flow fan located in Chalk Cliffs near Nathrop, Colorado, USA where the alluvial fan toe is periodically eroded by Chalk Creek.

Figure 2.1: Example of fan-toe truncation by a trunk stream. This fan is located in Chalk Cliffs near Nathrop, Colorado.

Physical modelling has a strongly rooted history in alluvial fan research. Early research reported analog models, models relying on the *similarity of processes approach* (Paola et al., 2009), that exhibited many of the fundamental features and processes (i.e., avulsions, lateral migration, channel entrenchment, channelization, and sheetflow) present in natural alluvial fans (Hooke, 1967; Hooke, 1968; Schumm, 1977; Hooke and Rohrer, 1979; Schumm et el., 1987). Later experiments expanded on these fundamental findings and methods. Effects of allogenic processes (e.g., Hooke and Dorn, 1992; Whipple et al., 1998; Paola et al., 2001; Sheets et al., 2002; Martin et al., 2009; Guerit et al., 2014) and autogenic processes on evolution of fluvially dominated alluvial fans has been widely studied (Hoyal and Sheets, 2009; Clarke et al., 2010; van Dijk et al., 2008, 2009, 2012), and to a lesser degree debris-flow dominated alluvial fans (De Haas et al., 2016). A general model of alluvial fan evolution has been accepted from these modeling experiments. The evolutionary model describes periods of channelized flow lead to fan progradation via the formation of depositional lobes until the channel begins to backfill toward the fan apex. After the channel is backfilled to a point where the channel can no longer contain flows, the fan avulses. A new fan segment is generated and unconfined aggradation takes place until channelization begins and the process is repeated.

However, a vast majority of the fans and deltas developed and analyzed via physical models use scenarios where the alluvial fans develop in an environment where there is unlimited accommodation space. However, many alluvial fans experience toe erosion from trunk streams flowing along the valley they form in (Harvey, 1984; Calvache et al., 1997; Viseras et al., 2003; Robustelli et al., 2005; Weissmann et al., 2005). The lack of accommodation space in these alluvial fan evolutionary scenarios would limit the applicability of progradation and backfilling model presented above. Alluvial fans with limited longitudinal accommodation space cannot prograde and therefore, are likely to superelevate as more material is deposited on the alluvial fan during aggradational phases. Superelevation of the active sector of deposition on a fan surface leads to a critical state near the fan apex which allows for avulsion. Bryant et al. (1995) found that as sedimentation rates increase, less sediment is needed to trigger an avulsion and overall fan slope increases. Hooke and Rohrer (1979) found that the active sector on their experimental debris-flow fan is superelevated as deposition occurs on one area for an undetermined amount of time, leading to a topographically higher surface than surrounding surfaces. This super elevation eventually causes avulsion to occur along the interface between these ‘high’ and ‘low’. This pattern is also insinuated from TLS monitoring of a telescoping fan near Nathrop, Colorado (Wasklewicz and Scheinert, 2016) (Figure 2.1).

The supposition of superelevation as a precursor to avulsion and as an autogenic control of alluvial fan evolution needs to be further validated. These findings have both scientific merit and applied implications as they provide critical information on shifts in the loci of deposition on alluvial fans, which is a major hazard that places humans and infrastructure at risk. Therefore, the purpose of the current study is: (1) generate an autogenically derived debris-flow fan under unlimited accommodation space that can be compared and contrasted with an (2) autogenically derived debris-flow fan under limited accommodation space. Data collected from the evolution of these alluvial fans is used to compare whether limited longitudinal alluvial fan accommodation space changes the autogenic processes responsible for the development of a new alluvial fan segment. The current hypothesis is that frequent fan-toe removal on autogenically controlled debris-flow fans results superelevation of the active fan segment, rather than cyclic channelization and backfilling, will lead to avulsion.

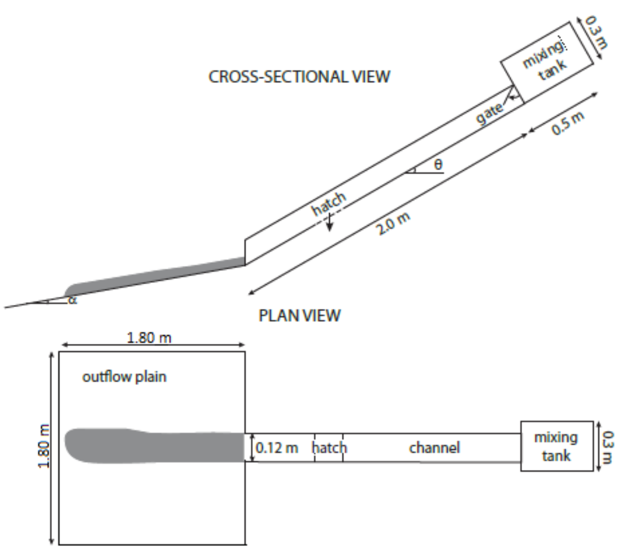

Figure 2.2: Sketch of experimental laboratory setup. Adapted from De Haas et al. (2016).

Methods

Laboratory Setup and Fan Generation

The experimental fans follow a similar set-up and design to De Haas et al. (2016). An in-house constructed mixing tank releases a debris-flow into a flume, simulating a feeder channel, whereby the debris is then transported onto the outflow plain (Figure 2.2). Extrinsic factors remained constant in both experimental fans. The debris-flow mixture consisted of 1,650g water, 288g kaolinite clay, 1,010g fine sand, 2,837g coarse sand, and 865g gravel. The sediment-water mixture varies slightly from De Haas et al. (2016) in that our debris-flow mixture contains 150g more water. Additional water was used in our experiments to expand the runout length of the debris-flows and enlarge the fans to enhance the potential for measuring multiple avulsions (personal communication with Dr. de Haas). The addition of 150g of water was also validated by testing other sediment ratios and water volumes to determine which combination led to a comparable debris-flow composition and yielded morphometrically similar results to De Haas et al. (2016).

Experimental fans were formed over many individual flows, which is consistent with alluvial fan development in natural settings. Each debris-flow was created using the following process: (1) each portion of the debris mixture was weighed; sediment was roughly mixed by hand to ensure clay did not stick to sides of the bucket; (2) sediment mixture was poured into the opening of the mixing tank, followed by the water; (3) total debris mixture was manually agitated for approximately 20 seconds; (4) the mixing tank gate was opened pnuematically by a manually operated switch; (5) debris is released into the flume and is transported onto the outflow plain; (6) 1.5 seconds after the gate is opened, a hatch located in the bottom of the flume 0.75 m from the gate, preventing debris-flow tailwater from entering the outflow plain and obscuring fan morphometry and; (7) the debris-flow deposits were allowed to dry for 2-3 hours with one portable fan directed at the fan apex and another directed at the active fan section.

Unlimited Accommodation Space vs. Limited Accommodation Space

Two experimental fans were generated for this study. First, a debris-flow fan with unlimited longitudinal accommodation space was generated with the previously described laboratory methods. A second fan was generated to simulate limited accommodation space. Limited accommodation space was achieved by removing all deposited material at distance greater than 95cm from the fan apex. This distance was informed by the initial experimental alluvial fan with unlimited accommodation space where all autogenic avulsion cycles were detected prior to 95cm from the apex. While fan-toe erosion in natural environments is a common scenario and caused by adjacent streams, here it is represented as the manual removal of sediment surpassing the cutoff length. A straight cut and removal of all sediment at 95cm to the end of the each debris-flow was done after each debris-flow event. Our experience at Chalk Creek indicates each debris-flow consistently plug the channel and are removed by the stream overtopping and eroding these plugs (Scheinert et al., 2012; Wasklewicz and Scheinert, 2016). We recognize a straight cut and removal of sediment below 95cm is a simplified view of the fan-toe erosion by a trunk stream. Wasklewicz and Scheinert (2016) note a more complex response in the toe-erosion where not only are the plugs being removed, but other portions of the alluvial fan toe eroded as the trunk stream channel shifts in response to the trunk channel aggradation. However, the approach does adequately simulate the process of alluvial fan toe erosion and provides “best” approximation of limited accommodation associated with an adjacent trunk stream.

Data Acquisition and Analysis

A Leica P40 laser scanner in a nadir-looking position was placed above the outflow table and recorded high-resolution topography (3mm point spacing) after every debris-flow. Four black and white targets were affixed at each corner of the outflow table and four additional targets were dispersed evenly on the walls of the laboratory. The nadir-looking positioning of the scanner allowed a single scan position per debris-flow. In order to resolve any differences in the non-fixed scanner location, target locations were used in the registration process conducted within Leica's Cyclone software with all registrations having no more than 2mm of error. Registered point clouds were processed into 3mm resolution digital elevation models using LAStools. All subsequent analyses were conducted in ArcGIS 10.4.

Nine planimetric profiles are spaced 10cm apart over the length of the limited accommodation space fan, beginning 5cm from the fan apex and ending approximately 10cm before the cut-off. No additional planimetric profiles generated for the unlimited accommodation space fan are included here for two reasons; first, to maintain comparability between the two fans and second, profiles beyond approximately one meter reveal information that is well represented in the nine profiles presented here. Deposit outlines were generated for each debris-flow event by manually digitizing a line feature around the perimeter of visible changes in elevation on DEM of difference (DoD) surfaces. DoD surfaces are derived by subtracting the DEM of the outflow plain prior to a debris-flow from the DEM of the outflow plain after the debris-flow (Wheaton et al., 2010). These methods offer two perspectives of spatially and temporally complete fan evolution.

Longitudinal profiles are digitized on a ‘phase by phase’ basis where the profile is digitized along the center line of the active channel during phases of backfilling or prior to avulsion events. The center line is visually approximated based on the deposit outlines for which each profile represents. Channel slope was measured in 5cm segments along the active channel center line. In-channel volumetric change is sampled along the active channel center line within abutting circles that are 5cm in diameter. Volumetric changes are derived by multiplying elevation changes from DoDs by the DEM cell area (Wheaton et al., 2010).

Results

Unlimited Accommodation Space Fan Evolution

The unlimited accommodation space fan (henceforth abbreviated to ULAcdS fan) was terminated after the fifty-sixth debris-flow due to channel backfilling reaching the hatch on the channel bed. This fan persisted through two avulsion cycles. Each cycle was characterized by phases of channelization and backfilling in the distal half of the fan that resulted in lateral growth until the fan avulses and the next avulsion cycle began with the formation of a new fan segment.

The first avulsion cycle began at approximately flow three after flow two overtopped flow one completely; flow three was contained completely inside flow two and channelization was initiated. Flow four remained almost completely channelized except for a 20cm length of the right side (looking up-fan) located between 50 and 70cm from the fan apex that was overtopped and expanded a maximum of 5cm. Runout length increased considerably and extended off the edge of the outflow plain. Flow four also saw the beginning of lateral expansion on both sides of deposits located in the first

25cm from the fan apex. This expansion was initiated by a lack of constricting lateral levees, and persists until such a time that conditions are favorable for such features to form. Flow five exhibits similar runout length as the previous flow, with a small amount of debris running off the edge of the table. The channel overflow area from flow four expanded laterally to a maximum of approximately 8cm between 64 and 77cm from the fan apex, after which the remainder of the right side of the deposit extending toward the fan toe was overtopped and expanded an average of 2cm laterally. The left levee remained intact and migrated laterally toward the right side of the outflow plain (Figure 2.3 a).

Flow six had a greatly reduced runout distance as the flow backfilled the channel and more of the flow volume was diverted toward the overflow area detailed in flows four and five, marking the creation of a new flow path (Figure 2.3 a). Flows seven and eight continued to backfill the channel while preferentially depositing an increasing volume of debris toward the newly developed path, their left levees laterally migrating toward the right (Figure 2.3 a, b).

Flow nine behaved much the same as the two previous flows with one major exception. A new section on the right side of the deposits extending from 25 and 70cm from the fan apex was overtopped and expanded laterally an average of 5cm, marking again the creation of a new flow path. Flows ten through twelve expanded on this new path while maintaining comparable runout distances. Flow twelve also experienced channel overflow over the left levee, averaging approximately 2cm lateral expansion, located between 25 and 75cm from the fan apex (Figure 2.3 b). Flows thirteen through eighteen continued to expand and channelize the newest flow path while backfilling and

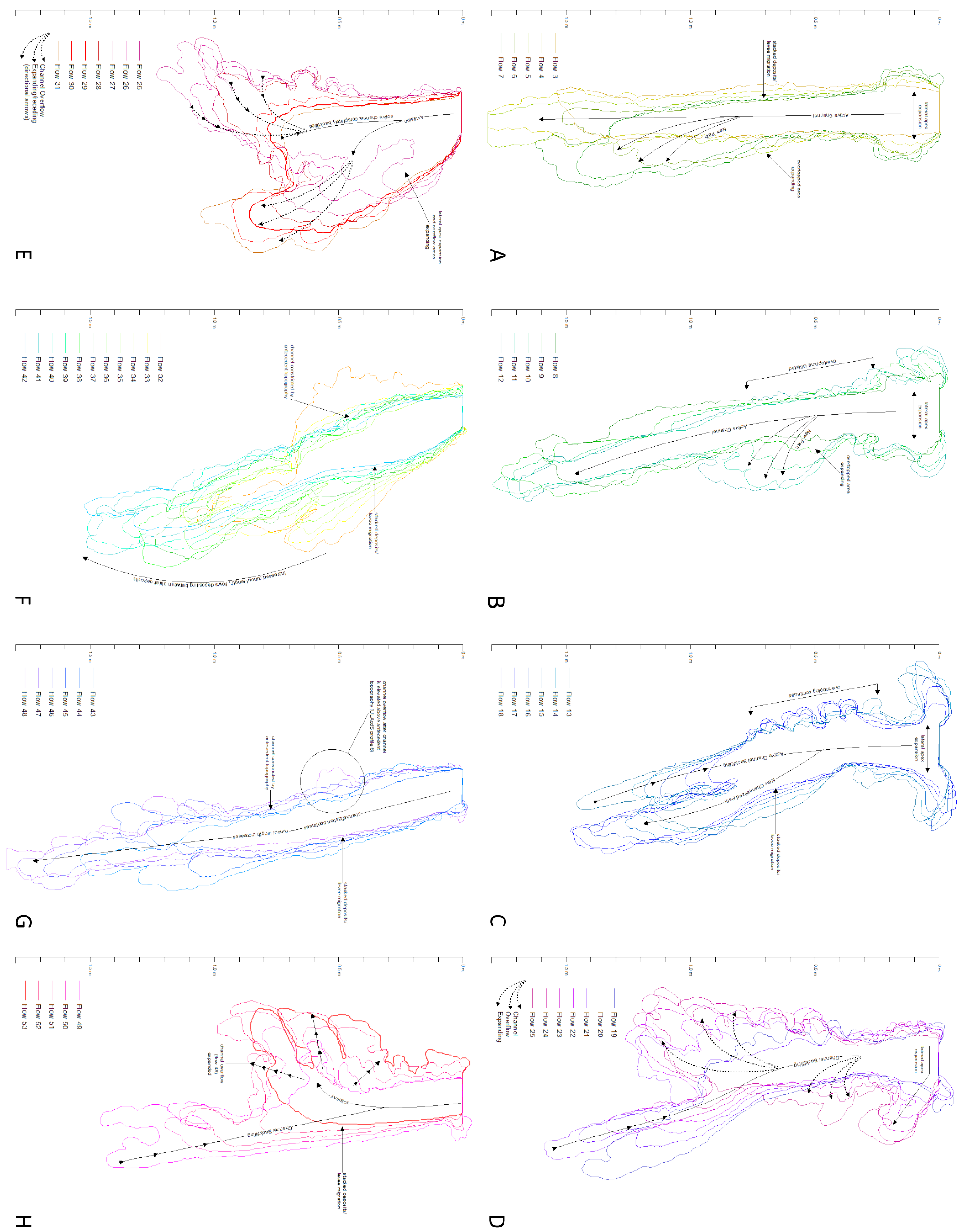

Figure 2.3: Deposit outlines illustrating the evolution of the unlimited accommodation space fan.

abandoning the previous. As flows channelize, the channel becomes increasingly narrow as the right levee migrates toward the center of the fan. During this time period, channel overflow over the left levee was continued, however the lateral expansion in this area only reached a maximum of approximately 3 – 4cm (Figure 2.3 c).

Flows nineteen and twenty expanded the channel overflow over the left levee. Flows twenty-one through twenty-five increased lateral apex expansion on the right side as well as lateral and longitudinal expansion of the channel overflow area over the left levee. During flow twenty-one, the active channel formed a depositional end lobe between older deposits, shifting laterally in the process; subsequent flows backfilled the main channel until flow twenty-five when it was completely buried. During flow twenty-three, a section of the right levee between 20 and 50cm from the fan apex experiences channel overflow which is expanded through flow twenty-five (Figure 2.3 d). During flows twenty-six through twenty-eight, the flow over the left levee recedes until complete abandonment as the flow over the right levee and near the channel apex is expanded and merges to form a new, unchannelized flow path (Figure 2.3 e).

The beginning of the second autogenic avulsion cycle began with flow twenty-nine; at this time, the left levee is re-established as it restricts flow from depositing on the left side of the fan (Figure 2.3 e). Flows thirty through forty-seven became narrower as they channelized and in turn ran out over longer distances, all the while migrating laterally toward the center of the fan. The left levee remained relatively motionless in the apex to mid-fan portion of the fan during this time period as the active channel was restricted by antecedent topography (Figure 2.3 f, g; Figure 2.6). Flow forty-eight experienced the longest runout distance in this avulsion cycle, running over the edge of the table. Beginning approximately 38cm from the fan apex, breaching over the left levee occurred and extended 65cm toward the fan toe (Figure 2.3 g). This expansion continued during flows forty-nine through fifty-two as the active channel backfilled and the right levee continued to migrate toward the center of the fan (Figure 2.3 h). Flow fifty-three marked the end of the second autogenic avulsion cycle as the active channel backfilled and the flow avulsed toward the left side of the fan. Deposition continued down the newly defined path until the experiment was terminated after flow fifty-six (Figure 2.3 h).

Limited Accommodation Space Fan Evolution

The second experimental alluvial fan (henceforth abbreviated to LAcdS fan) was terminated after the fifty-ninth debris-flow as the feeder channel backfilled to the tailwater hatch. While the LAcdS fan did consist of fifty-nine total debris-flow events, only the first thirty-six are presented here for analysis. The thirty-seventh debris-flow consisted of approximately 200 fewer grams of water due to improper measurement. While subsequent flows consisted of the cited water-sediment mixture, the error during flow thirty-seven prevents complete certainty that the fan dynamics following this flow are only formed through autogenic processes. Although the LAcdS fan experiment length is shorter than that of the ULAcdS fan, important differences in the autogenic processes responsible for new fan development are identifiable.

The LAcdS fan displayed two full autogenic avulsion cycles and appeared to be well into the third avulsion cycle during the thirty-sixth flow. These cycles were characterized by phases of channelization and vertical accretion followed by avulsion whereby the process began again with the generation of a new fan segment.

The first avulsion cycle began approximately with flow five. The first four flows stacked on top of each other until full channelization was achieved during flow five.

Flows six through eight remained channelized. Lateral expansion near the fan apex almost completely similar to that mentioned in the ULAS fan description was also initiated at this time, extending 20cm longitudinally from the apex and expanding an average of 5cm laterally on the left side (looking up fan) and 10cm on the right. Aside from the area affected by this expansion, the remainder of the channel narrowed slightly with each flow as channelization continued. Flow nine remained almost completely channelized except for a 15cm length of the left levee located between 20 and 45cm from the fan apex that was overtopped as well as a 7cm length of the right levee located between 22 and 29cm from the fan apex (Figure 2.4 a).

Flow ten marks the beginning of the second autogenic avulsion cycle (Figure 2.4 a). The left levee was almost completely overtopped down the length of the fan during flow ten and only the last 12cm of runout remaining channelized. Flows eleven through fourteen continued to overtop the left levee, forming a new flow path and becoming increasingly channelized with the creation of new lateral left levee. Both levees migrate medially; the left levee experiences a higher rate of movement. Debris continues to travel down the previous channel despite the new flow path. During flow thirteen, the lateral expansion on the right of the apex is abandoned but continues to grow on the left side (Figure 2.4 b).

Flow fifteen is the first instance where runout surpasses the erosion simulation cut off at a new location (Figure 2.4 b). Flows sixteen through nineteen remain mostly channelized and lateral migration of the left levee toward the center of the fan continues. A 25cm section of the right levee located between 70 and 95cm from the fan

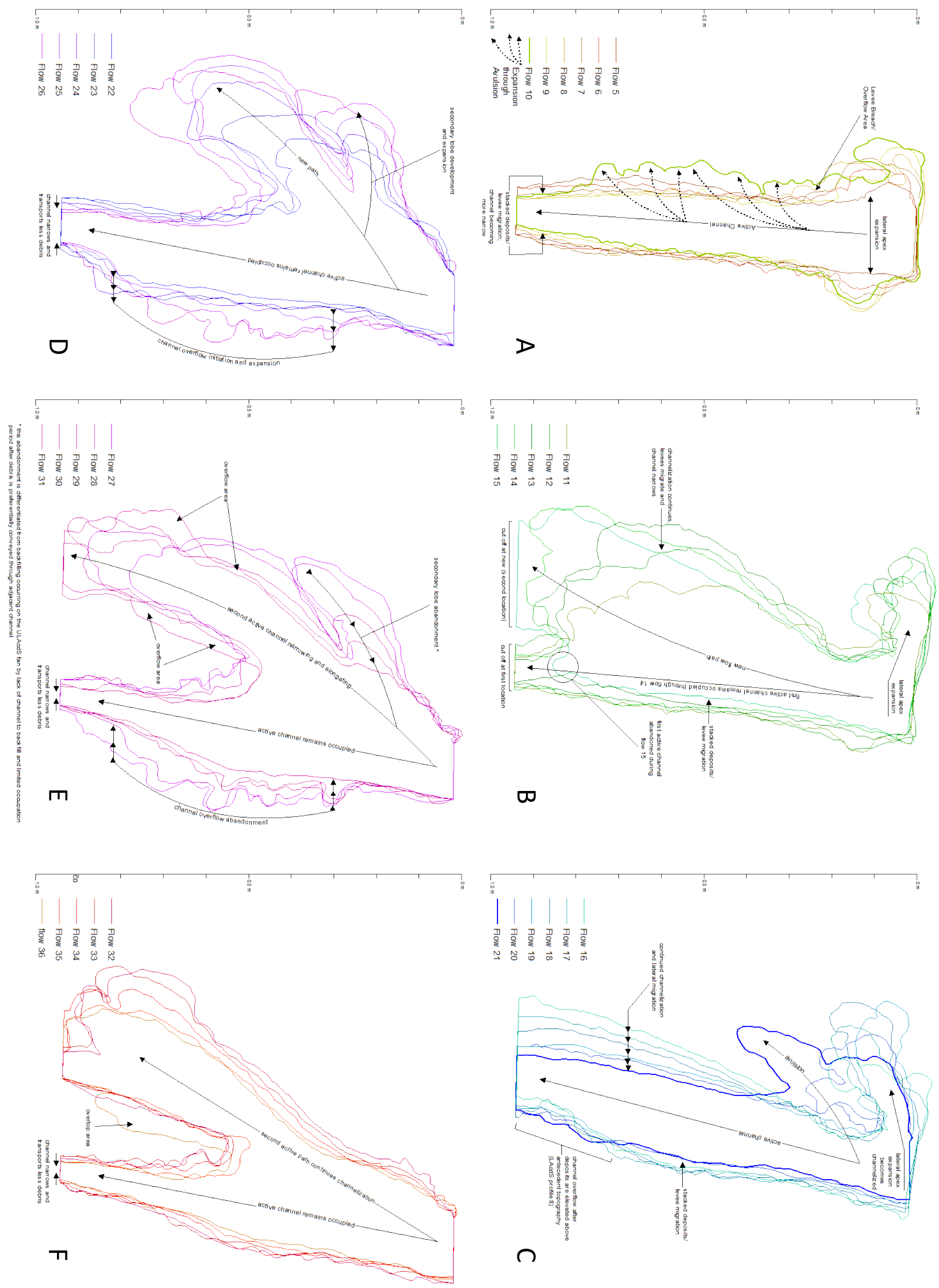

Figure 2.4: Deposit outlines illustrating the evolution of the limited accommodation debris-flow fan.

apex is overtopped. Flow twenty remains channelized except for a section of the left levee breached between 10 and 24cm from the apex. During flows fifteen through twenty the debris contributing to the lateral expansion on the left of the apex become channelized (Figure 2.4 c).

Flow twenty-one initiates the beginning of the third autogenic avulsion cycle (Figure 2.4 c). During this flow, the left lateral expansion merges with debris overtopping the left levee, initiating a new flow path. The left levee breach expands to 32cm in length, starting from the beginning of the levee located approximately 10cm from the fan apex.

Flows twenty-two through thirty expand the new flow path and channelization begins, propagating debris over longer distances (Figure 2.4 d, e). A secondary lobe is generated from the left side of the flow path during flow twenty-four. This lobe expands through flow twenty-six and is eventually abandoned completely during flow thirty-one. Flow twenty-nine is the first flow in the third avulsion cycle to surpass the erosion simulation cut off at a new location. Throughout the creation and persistence of this new flow path, debris continues to travel down the previous channel (the channel extending straight out from the fan apex); this older channel becomes narrower with time and transports a decreasing amount of debris. During flow twenty-three the right levee (bordering the previous channel) is overtopped an average of approximately 2 cm between 15 and 85 cm from the fan apex. This overflow area is expanded through flow twenty-seven where lateral spreading peaks at an average of 5cm. By flow thirty, this overflow area is abandoned and the right levee is re-stabilized close to its prior position (Figure 2.4 d, e).

Flow thirty-one overtops the main active channel (youngest channel) on the left and right sides in the distal half of the fan (Figure 2.4 e). Flow thirty-two expands on these breaches slightly, however flows thirty-three through thirty-five begin to channelize once again. This short-lived expansion is attributed to the increase in debris volume directed toward this channel after the secondary lobe is abandoned during flow thirty-one. The extent of the data presented here ends with flow thirty-six during which the right side of the active channel was breached once again (Figure 2.4 f).

Comparing and Contrasting Limited and Unlimited Accommodation Space Fans

Both fans share similar morphometry and processes regardless of the amount of accommodation space. Both fans undergo extended periods of channelized flow. The channelization phase of the avulsion cycle begins when debris is redirected from the active channel as overtopping of existing levees takes place. This debris forms a poorly

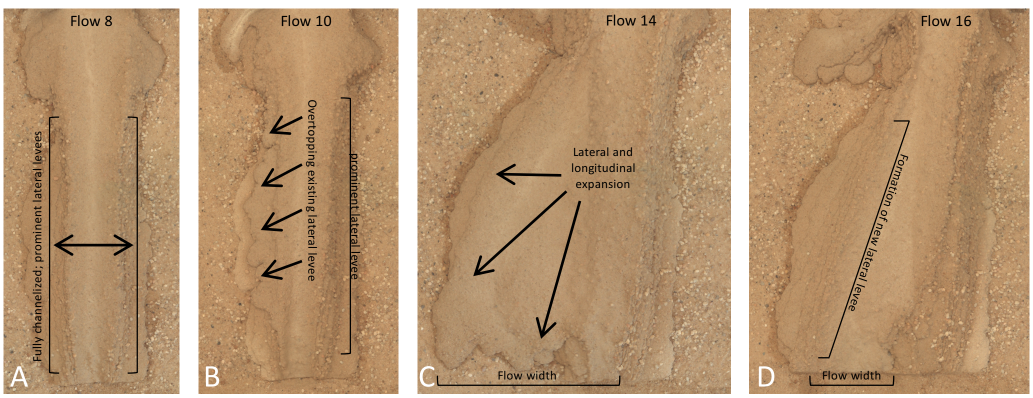

Figure 2.5: Point cloud data from the LAcdS fan overlaid with color images from the P40 scanner. Images A - D illustrate phases of channelization, new segment generation, and lateral migration of stacked deposits.

sorted, lobate deposit (Figure 2.5 a, b). Subsequent flows contribute an increasing volume of debris that continues to overtop the levee and the unchannelized deposit is expanded both laterally and longitudinally (Figure 2.5 c). Eventually coarse material forms lateral levees on either side of the overtop area and channelization is initiated whereby flows become narrower and more elongated (Figure 2.5 d).

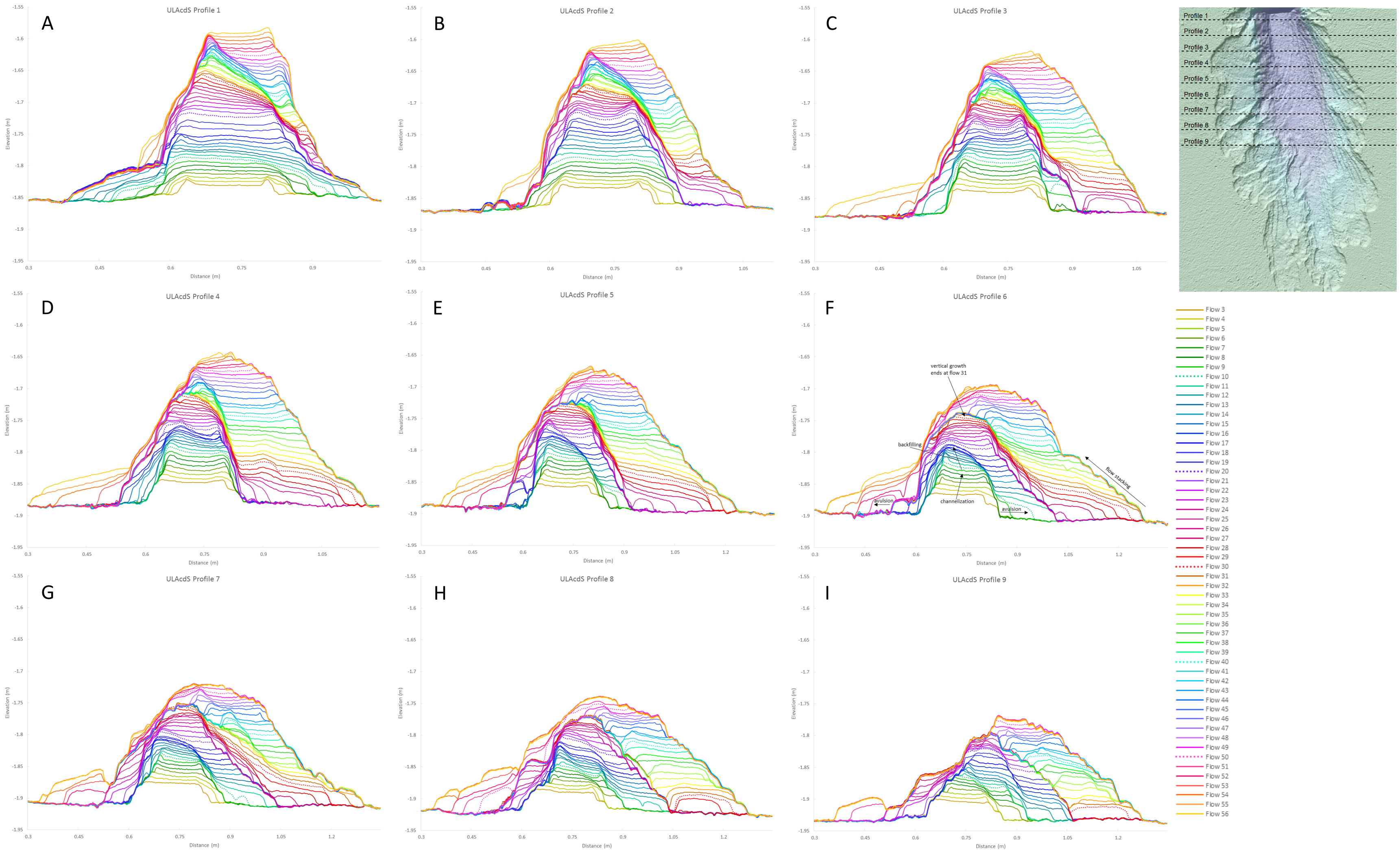

Figure 2.6: Planimetric profiles for the unlimited accommodation space fan.

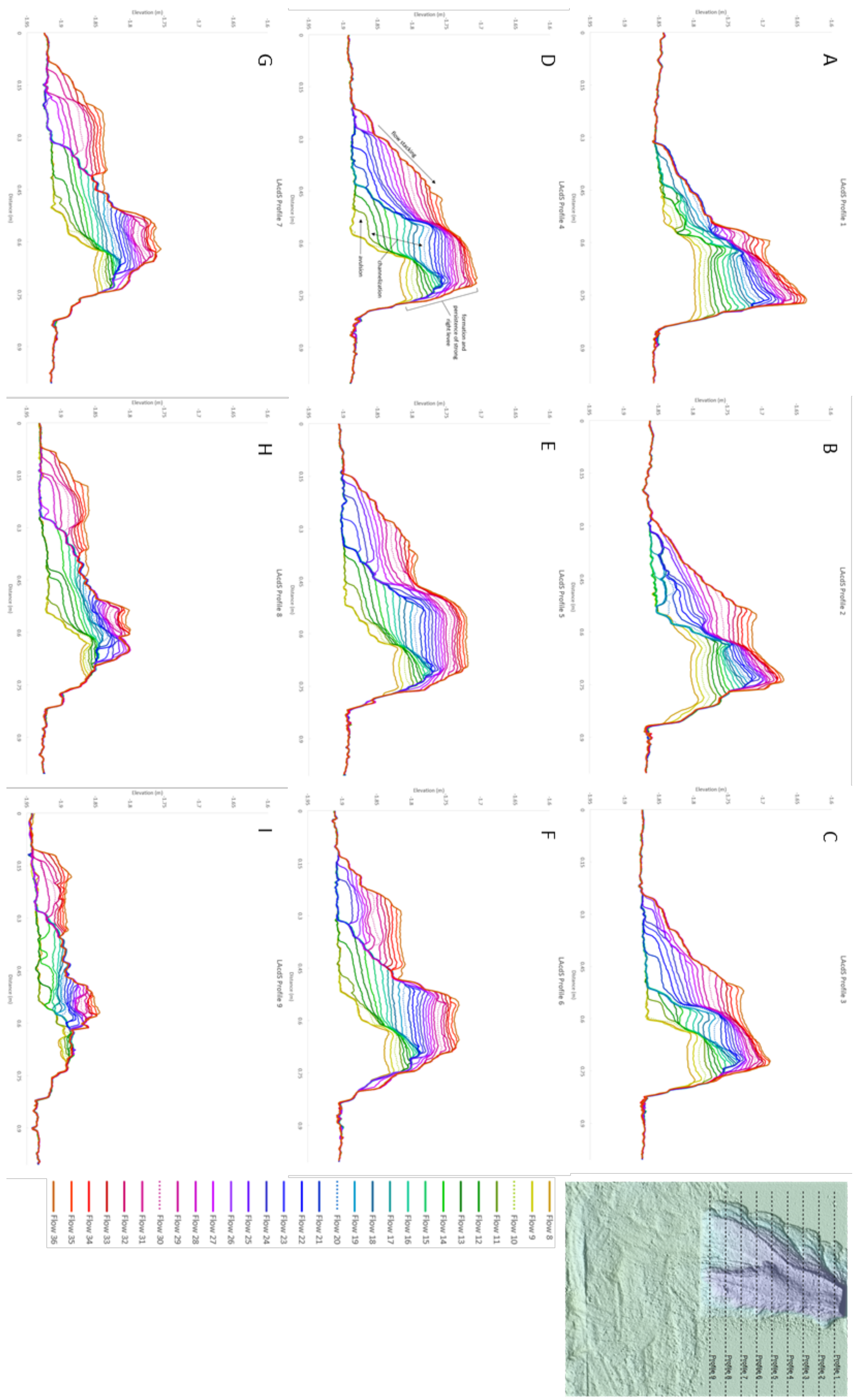

Figure 2.1: Planimetric profiles for the limited accommodation space fan.

While the two fans do share visually discernable similarities, analysis of planimetric and longitudinal profiles as well as slope and volumetric calculations revealed a series of fundamental differences. One of the most immediately evident differences in fan development is a distinct lack of channel backfilling in the LAcdS fan. Visible in the planimetric profiles generated across the fan surfaces, ULAcdS fan profiles transition from concave to plano-convex during episodes of backfilling while LAcdS fan flows are almost consistently channelized (concave) throughout the experiment (Figures 2.6, 2.7).

Deposition, and as a result vertical accretion, is decreased and eventually abandoned where channels have backfilled on the ULAcdS fan. This is illustrated in planimetric profiles where, as a section of profile transitions from concave to plano-convex, the profile lines are closer together and eventually there is no discernable difference as the lines are bunched together as vertical growth ends (ex. Figure 2.6 f). Note that this pattern only applies to the section of the profile that has transitioned from concave to convex and that vertical accretion is occurring elsewhere on the fan. Planimetric profiles of the LAcdS fan do not exhibit this pattern. Even after the fan avulses, vertical accretion continues in the same locations and is not abandoned. This is

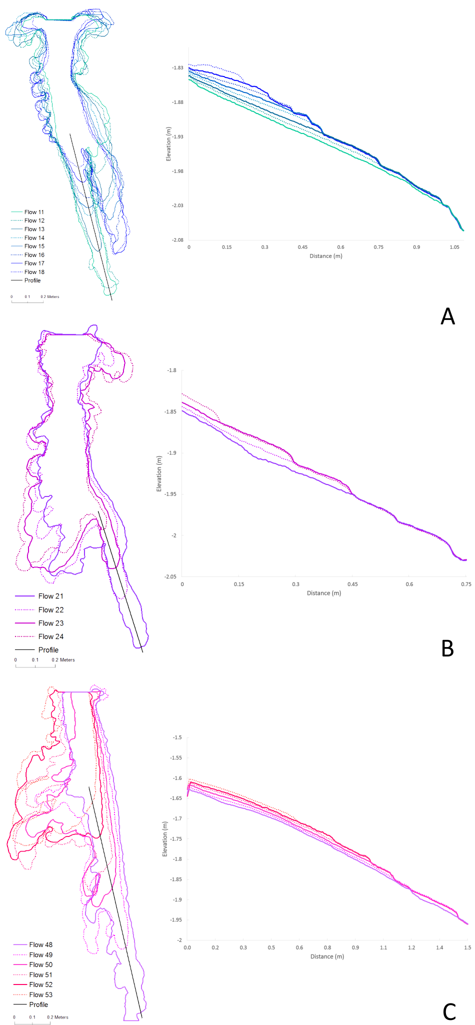

Figure 2.2: Longitudinal profiles generated along the center lines of channels through the backfilling process on the ULAcdS fan.

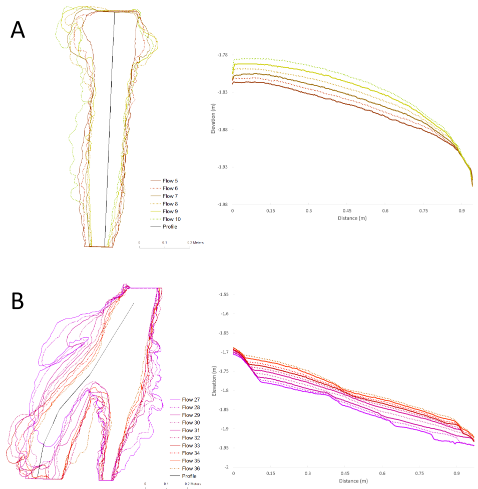

Figure 2.9: Longitudinal profiles generated along the center lines of active channels on the LAcdS fan during flows 5 - 10 (A) and 27 - 36 (B).

illustrated particularly well in Figure 2.7 d where the right levee continues to grow vertically through the avulsion and channelization of a new fan segment on the left side of the profile. Note that although vertical accretion is present over the entire profile, the right levee is growing at a slower rate than the newly channelized segment on the left side shown through smaller vertical spacing of profile lines on the right side of the fan compared to the left (Figure 2.7 d).

Longitudinal profiles coupled with deposit outlines are another way to visualize the presence and absence of backfilling on the ULAcdS and LAcdS fans, respectively. The ULAcdS fan exhibited three extended phases of backfilling for which longitudinal profiles were generated. These profiles display stacked deposits decreasing in runout length punctuated by, in most cases, a visible change in slope indicating the presence of a prominent depositional lobe (Figure 2.8). Deposit outlines and longitudinal profiles generated for the LAcdS fan, on the other hand, illustrate stacked deposits that remain channelized and are not backfilled (Figures 2.4, 2.7). While the longitudinal profile digitized down the center line of the first active channel on the LAcdS fan does not reveal channel backfilling, it does indicate another important process (Figure 2.9 a). There is a drastic decrease in vertical accretion located approximately along the last 25 cm of the channel. This observation is attributed to an increase in slope in this area, generated and exacerbated by the limited accommodation space imposed during this experiment (Figure 2.10 a).

Slope along the center line of the active channel on the LAcdS fan generally increases with distance from the fan apex (Figure 2.10 a, b). As the fan approaches avulsion during flows ten and twenty-one, channel slope increased in the distal half of the channel while decreasing in the proximal half. Of particular interest are the points where avulsion is first initiated, approximately between 15 and 25cm along the center line for the first avulsion and between 20 and 35cm for the second avulsion. These sections both experienced decreases in slope approaching avulsion (Figure 2.10 a, b).

Measures of channel slope and volumetric change preceding avulsion on the ULAcdS fan further reflects the process of channel backfilling through drastic increases in slope coincident with end lobe formation and migration and incremental decline and absence of volumetric change (Figures 2.10 c, 2.11).

Deposition within the active channel on the LAcdS fan preceding avulsion is spatially and temporally variable (Figure 2.12). The most deposition occurs in the mid-

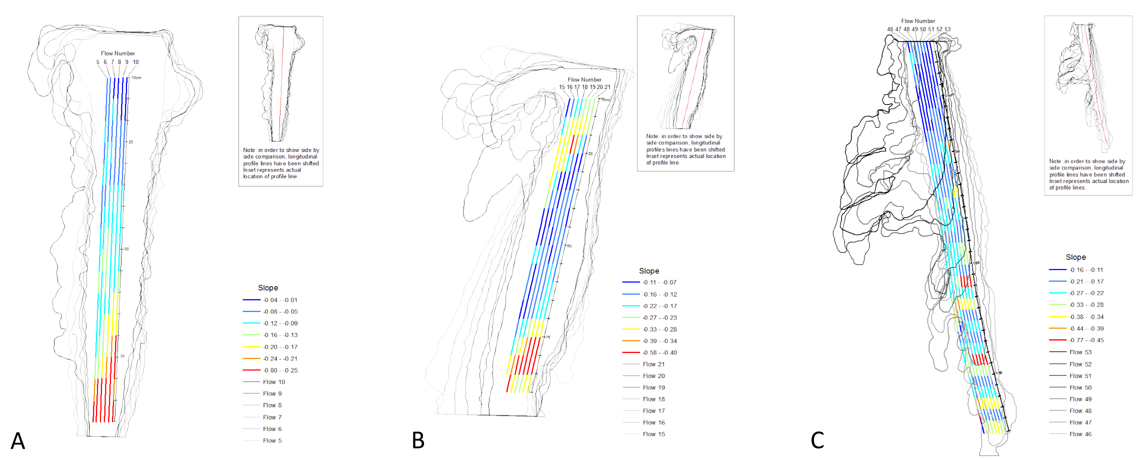

Figure 2.3: Longitudinal profiles generated along the center lines of the active channel were divided into 5cm intervals. Slope was calculated for each interval for each profile, spanning over flows 5 - 10 (A) and flows 15 - 21 (B) for the LAcdS fan and flows 46 -53 for the ULAcdS fan.

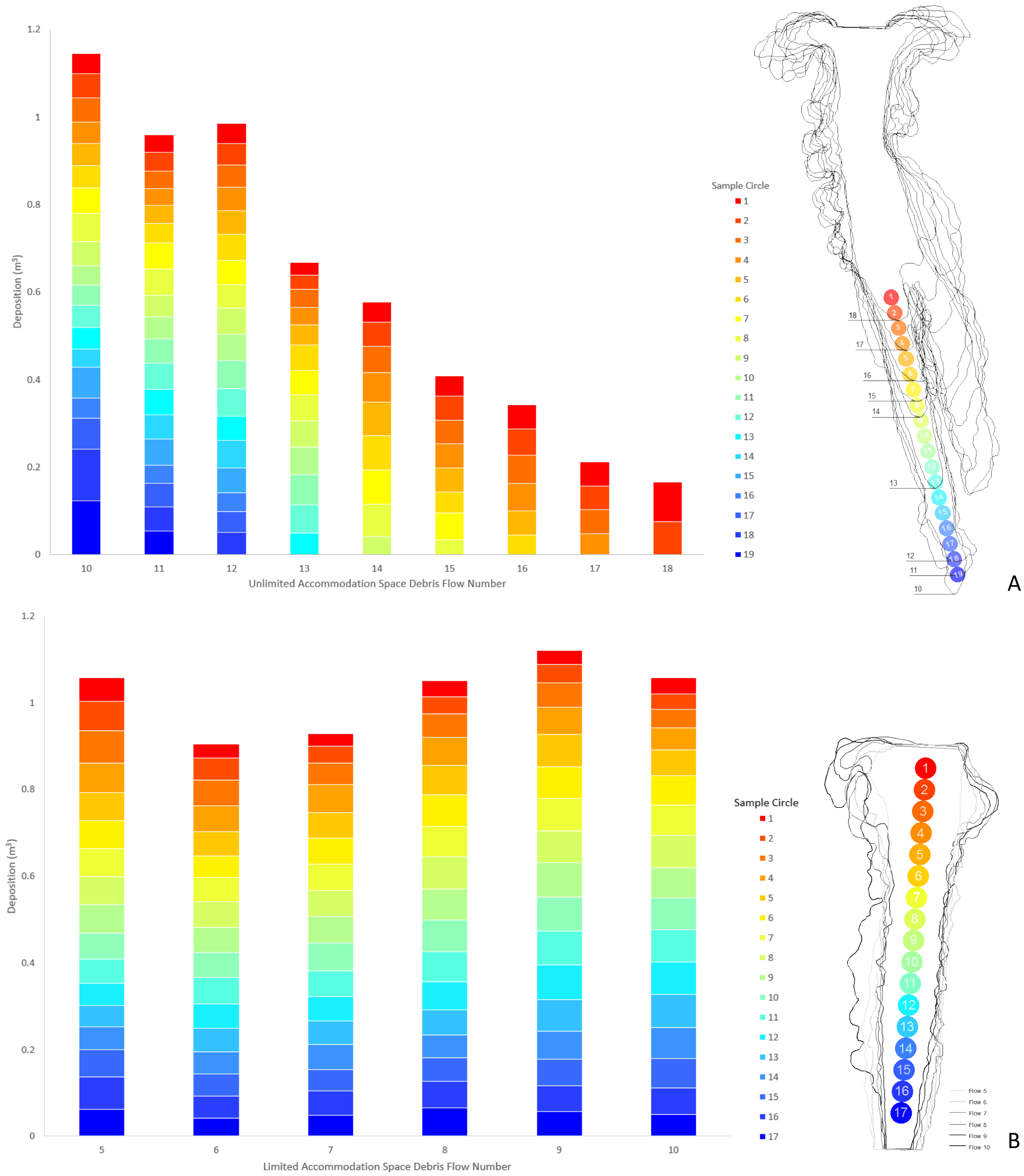

Figure 2.11: Volumetric changes within 5cm sample circles along the backfilling channel on the ULAcdS fan during flows 10 - 18 (A) and along the center line of the active channel for the LAcdS fan during flows 5 - 10 (B). These figures show that the active channel is backfilled on the ULAcdS fan following avulsion whereas deposition remains relatively consistent within the active channel on the LAcdS fan.

fan area while the least occurs near the cutoff. As the fan approaches avulsion during flows ten and twenty-one, in-channel deposition decreased in the distal portion of the channel while increasing in the mid-fan. Deposition culminates in sample circle four for flows five through ten and sample circles three and four for flows fifteen through twenty-one, approximately where avulsions are first initiated (Figure 2.12).

Discussion

The purpose of this research is to investigate whether limited accommodation space changes the autogenic processes responsible for avulsion and the development of a new alluvial fan segment. An underlying assumption associated with this research goal is the experimental fan developed with unlimited accommodation space behaves in accordance with the observed processes and responses reported in other studies, specifically De Haas et al. (2016). This section is divided into three subsections that investigate (1) the similarities and differences between the experimental fan created with unlimited accommodation space in these experiments and the fan developed by De Haas et al. (2016); (2) the processes surrounding autogenic avulsion on the LAcdS fan; and (3) the differences between avulsion mechanics on the ULAcdS and LAcdS fans.

Comparing and contrasting ULAcdS fan to De Haas et al. (2016)

The processes and responses observed on the ULAcdS fan were comparable to those reported in De Haas et al. (2016). The ULAcdS fan experiences two full autogenic avulsion cycles defined by phases of progradation and retrogradation. Progradational phases produce elongated deposits bounded by coarse-grained lateral levees, punctuated by well-defined end lobes. Retrogradational phases produce short and wide

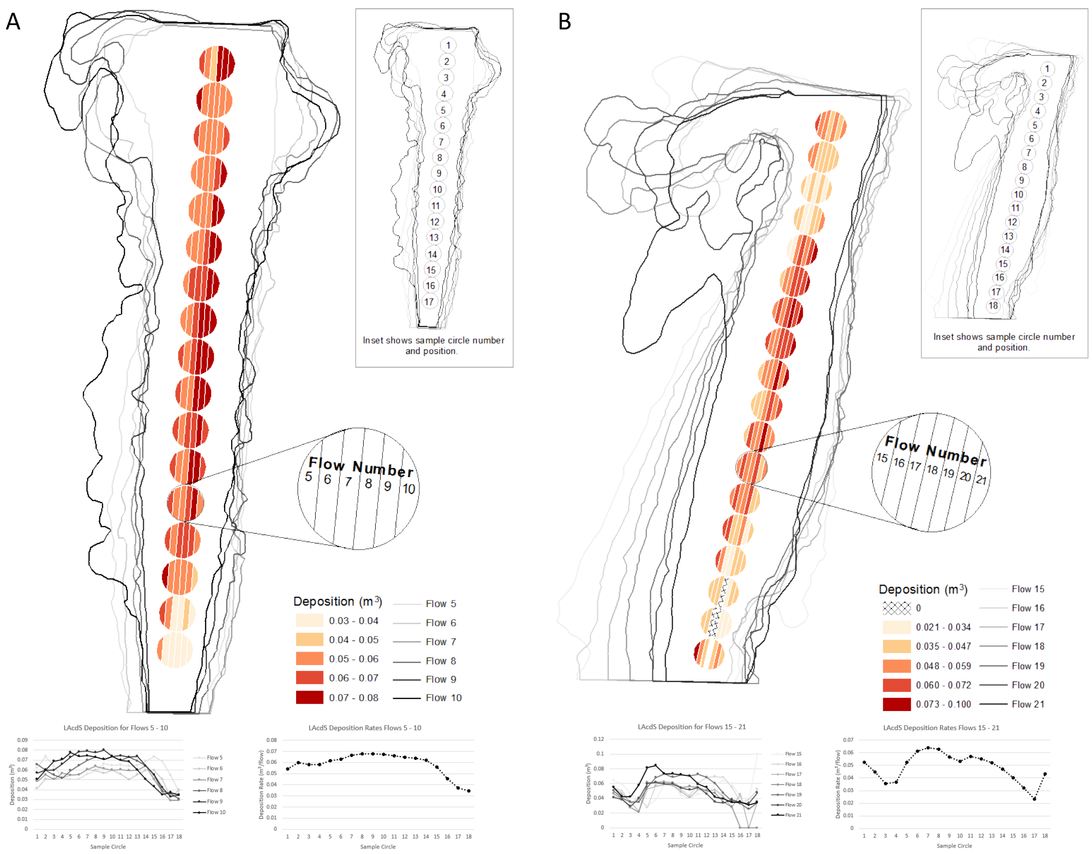

Figure 2.4: Spatial distribution of deposition within the active channel on the LAcdS fan during flows 5 - 10 (A) and flows 15 - 21 (B). Absolute deposition (left) and deposition rates (right) shown graphically at bottom.

deposits and following channel backfilling. Channel backfilling is exacerbated by upstream migrating depositional lobes of previous deposits.

Both the ULAcdS and De Haas et al. (2016) fans are driven by topographic compensation at different spatial and temporal scales as 'local' lows are targeted for deposition between avulsion cycles while fan-wide 'absolute' lows are targeted during avulsion cycles.

Both experiments ultimately result in similar landforms leading to the conclusion that the ULAcdS fan and the De Haas et al. (2016) fan are comparable. However, the following discussion details observed differences between the two fans, specifically differences surrounding the timing and processes of channel backfilling. De Haas et al.

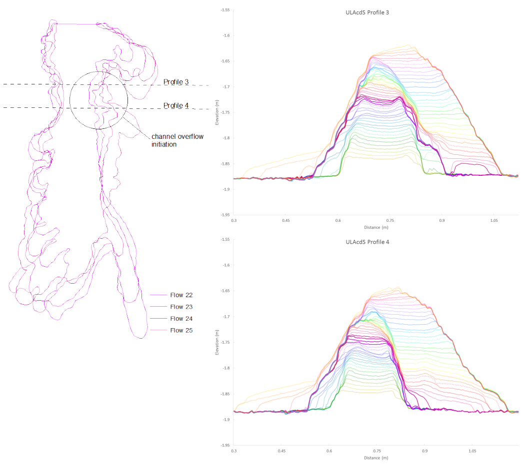

Figure 2.5: Example of local superelevation on the ULAcdS fan during flows 22 – 25.

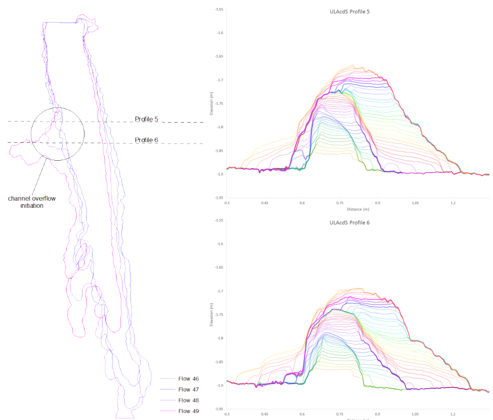

Figure 2.14: Example of local superelevation on the ULAcdS fan during flows 46 - 49.

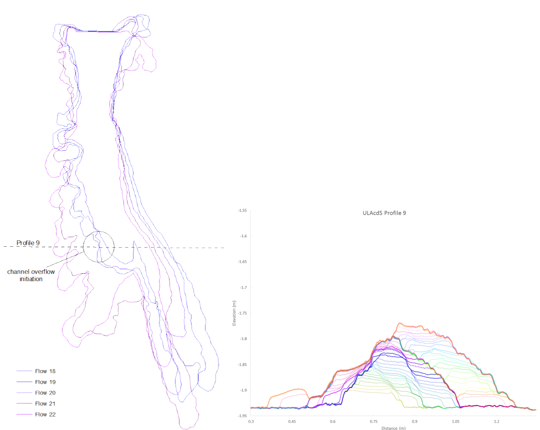

Figure 2.15: Example of local superelevation on the ULAcdS fan during flows 18 - 22.

(2016) report that after channelized deposits reach their maximum runout length, as limited by slope and debris flow volume and composition, channel backfilling is initiated *followed* by progressively short and wide deposits. On the ULAcdS fan, however, channel overflow leading to wide deposits occurs *prior to* and *during* channel backfilling.

Over the course of the ULAcdS fan experiment there were three well defined phases of backfilling: during flows thirteen through eighteen, twenty-two through twenty-five, and forty-nine through fifty-two. Phases of backfilling are initiated subsequent to channel overflow elsewhere in the channel (Figures 2.13, 2.14, and 2.15). The explanation for this behavior offered here is as follows: (1) as deposit runout length increases, the channel narrows as it is limited by debris volume, medially migrating lateral levees, and antecedent topography. (2) These factors in conjunction with the non-erosive nature of the experiments, cause local superelevation and subsequent channel overflow as in-channel sedimentation exceeds the barrier posed by antecedent topography. (3) As the channel overflow area is expanded, channel backfilling is initiated. (4) The new flow path is channelized and the cycle begins again.

Autogenic avulsion processes on an experimental debris-flow fan with limited longitudinal accommodation space

Limited accommodation space prevents depositional lobes from forming, as debris that would have comprised these lobes is transported out of the fan system via a stabilized channel that forms in the center of the fan surface. Clarke et al. (2010) report a similar process as on an experimental (fluvial flow) alluvial fan that is limited by a drainage channel located at the fan toe. In their experiment, an entrenched channel on the surface of the fan forms and stabilizes after the active channel extends to the drainage area, allowing an increasing volume of sediment to be efficiently transported out of the fan system. Although the LAcdS fan did not become entrenched, the formation and persistence of strong lateral levees accomplishes a similar process.

The creation of the stabilized channel is attributed to a feedback mechanism whereby in-channel accretion occurs more rapidly in the apex to mid-fan regions, resulting in a dramatic increase in slope in the distal region of the fan. As slope increases in the distal region, less in-channel accretion occurs and the channel is stabilized. This feedback can be observed visually through longitudinal profiles (Figure 2.9 a) and corroborated by slope (Figure 2.10 a and b) and volumetric (Figure 2.12) calculations.

Despite the absence of channel backfilling, the LAcdS fan, like the ULAcdS fan, evolves as the active channel narrows through time and migrates toward the center of

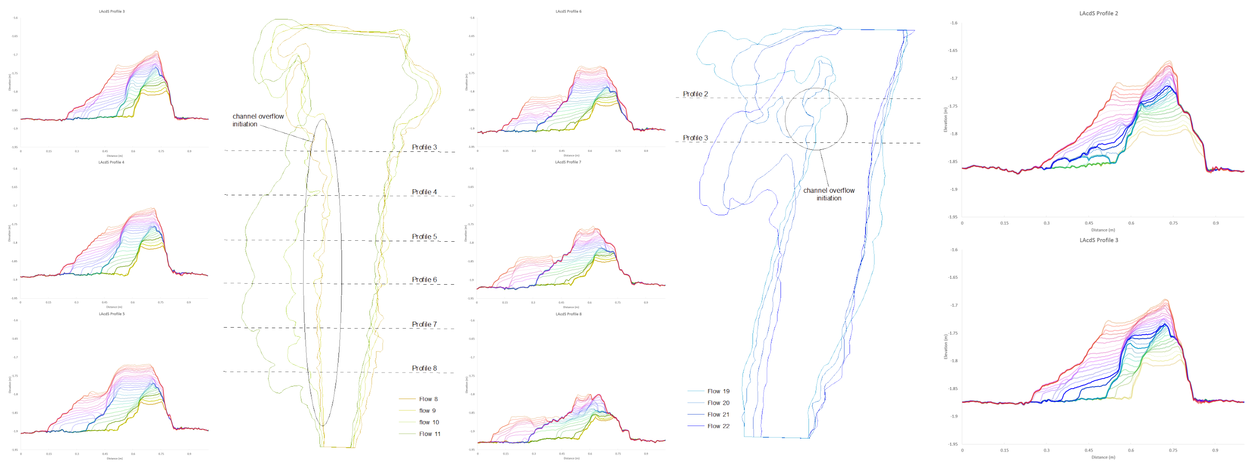

Figure 2.16: Examples of channel overflow on the LAcdS fan during flows 8 - 11 (left) and flows 19 - 22 (right).

the fan. Thus, autogenic debris-flow fan evolution under the limited accommodation space provided in these experiments can be summarized as follows: (1) The active channel narrows until a lateral levee is breached, initiating channel overflow. (2) Channel overflow is expanded and a new flow path channelizes, creating two active channels on the fan surface. (3) The newest flow path continues to channelize, migrating toward the center of the fan as it is narrowed by a lateral levee on one side and antecedent topography on the other. (4) Channelization and migration continues until the two active channels merge and the cycle repeats itself. Local channel narrowing and decreased channel capacity leading to avulsions on the LAcdS fan are illustrated in figure 2.16.

Comparing the ULAcdS and LAcdS fans

Autogenic avulsion on both experimental fans arises from phases of channelization that narrow active channels until the channel cannot longer contain flows. The point of channel overflow is typically caused by local superelevation above antecedent topography or channel capacity being exceeded before superelevaton can be achieved. This overflow initiates the development of a new flow path and channelization begins again. As channelization progresses, flow stacking promotes the gradual, medial migration of deposits. The difference in avulsion processes between the two fans revolves around what becomes of the active channel once channel overflow is initiated. On the ULAcdS fan, the channel is backfilled. The LAcdS fan maintains a stabilized channel because the debris that would have backfilled the channel is transported out of the system. These processes result in disparate topographic features that affect subsequent depositional processes. On the LAcdS fan, Channel backfilling creates an unchannelized, convex feature while the stable channel on the LAcdS fan maintains its concave, channelized structure. These features become important as the newly developed flow path channelized and migrates toward the center of the fan.

On the LAcdS fan, the unbreached levee of the stabilized channel continues to grow vertically as the channel continues to transport debris. This levee acts as a barrier that constrains flows as channelization progresses and the newly formed channel migrates toward the center of the fan (Figure 2.7 d). While the antecedent topography formed through backfilling on the ULAcdS fan also constrains flows through the channelization process, these features are more quickly over topped because of the lack of vertical growth after channel abandonment (example: Figure 2.6 f, Figure 2.14).

While it was not exhibited in these experiments, a logical assumption is the unaffected levee of the stabilized channel on the LAcdS fan will experience channel overflow as the active fan segment is superelevated, switching the locus of deposition from one side of the fan to the other. This process is demonstrated on the ULAcdS fan after the second avulsion (Figure 2.3 e, Figure 2.6). This process was unable to be observed due to the rapid backfilling of the feeder channel.

The results presented in this article show limited accommodation space eliminates the channel backfilling process and generates a stabilized channel in the center of the experimental debris-flow fan. Following the generation of a new fan segment, the stable channel continues to transport debris which leads to the vertical accretion of the unaffected levee. This continual vertical accretion prolongs the period in which one side of the fan is active, as compared to the ULAcdS fan, as the active channel capacity will be exceeded and avulsion will be initiated before the active fan segment is able to superelevate and transition the locus of deposition to an inactive fan sector. These findings agree with processes observed on Hooke and Rohrer’s (1979) experimental fan and field evidence from Wasklewicz and Scheinert (2015). These authors observe deposition occurring for an undetermined amount of time on one fan sector, initiating active sector superelevation and subsequent avulsion from topographically ‘high’ to ‘low’ areas.

Conclusions

Two experimental debris-flow fans were generated as a result of autogenic processes in order to compare autogenic avulsion mechanics on fans with unlimited accommodation space to fans with limited accommodation space. The research question investigates whether or not limited longitudinal alluvial fan accommodation space changes the autogenic processes responsible for the development of a new alluvial fan segment. The hypothesis that frequent fan-toe removal on autogenically controlled debris-flow fans will result in the superelevation of the active segment, resulting in shifts in the locus of deposition is rejected. Results from small-scale physical modeling experiments show that cycles of channelization, formation and persistence of a stabilized channel, channel narrowing and overflow, and avulsion result in the formation of new fan segments on a debris-flow fan with limited accommodation space.

The results from these experiments suggest that limiting the longitudinal accommodation space in which an autogenically controlled debris-flow fan is allowed to occupy fundamentally changes the fan's avulsion patterns. These results provide evidence for an explanation of debris-flow fan evolution alternative to the most widely accepted theory which can be summarized as cycles of channelization, backfilling, and avulsion.

CHAPTER 3: SUMMARY

Overview of experimental setup

The experimental fans were created in a laboratory setup following the design outlined in de Haas (2016). This setup (Figure 3.1) consists of an in-house constructed mixing tank (A) that releases the sediment mixture onto a flume (B), which simulates a feeder channel, whereby the debris-flow material is transported onto the outflow plain (C). The mixing tank is 0.3 m in diameter and 0.5 m long and is fitted with paddles and a hand crank used to manually agitate the sediment mixture for approximately 20 seconds before being released through a remote-activated, upward-swinging hatch into the channel. Another hatch (D), located on the channel bed, was opened 1.5 seconds after debris is released from the mixing tank to prevent the debris-flow tailwater from entering the outflow plain and obscuring fan morphology. The flow was allowed to dry for two to three hours while a portable fan (E) was directed at the apex. Channel dimensions are 0.12 meters wide by 2 meters long, positioned at a 30° angle relative to the outflow plain. The surface serving as the outflow plain is approximately 2 meters by 2 meters positioned at a 10° angle. This surface was covered with approximately one centimeter of the reference mixture, unconsolidated, without the clay and water. The bottom and walls of the channel were covered with 80 grit sandpaper to simulate natural channel roughness.

High resolution topographic data was collected using a Leica P40 laser scanner positioned above the outflow plain (Figure 3.1 F). The surface of the outflow plain was scanned at a 0.003m resolution after every debris-flow. Four black and white targets

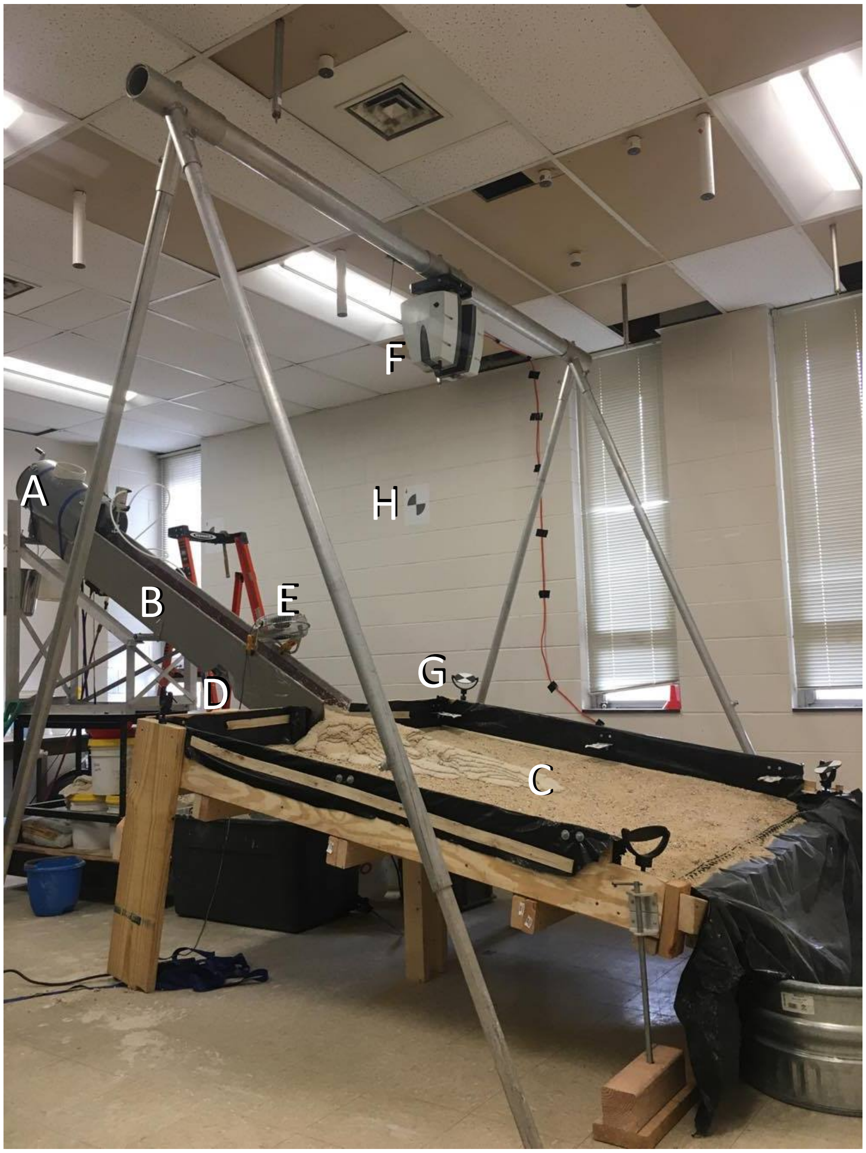

Figure 3.1: Diagram of the experimental laboratory setup.

were placed at the corners of the outflow plain (Figure 3.1 G) and four targets were spread uniformly around the laboratory (Figure 3.1 H). These targets were used to register the scan data in Leica's point cloud processing software, Cyclone, in order to align scans if the laser scanner or outflow plain moved. All registration errors were below 2mm.

Ability to replicate experimental fan in De Haas et al. (2016)

On a “large” scale, we see the same morphometric features identified by De Haas et al. (2016). The most commonly formed features included: levees, depositional lobes/snouts, and avulsions driven by these features. A similar number of flows occurred before the channel backfilled and experiment was terminated; Tjalling’s experiment lasted for 55 flows, the current study had 56 flows.

An additional 150g more water was the only modification to the specific concentration of the debris-flow mixture reported in De Haas et al. (2016). This concentration was settled upon after an extended period of trial and error. Sediment ratios and water concentrations were varied and the addition of 150g of water permit flows to maximize runout distance and to enhance the potential for measuring multiple avulsions (personal communication with Dr. de Haas). The debris-flows exhibited many of the same characteristics reported on the experimental fan created in De Haas et al. (2016).

Once the debris-flow mixture was settled, the experiment continued and was terminated after fifty-six flows when channel infilling reached the hatch at the bottom of the flume. The number of flows is comparable to the fifty-five debris-flows that comprised De Haas’ et al. (2016) fan, which herein will be abbreviated as DH fan. Both fans persisted through two full avulsion cycles. The ULAcdS fan avulsed during flows twenty-nine and fifty-three compared the avulsions occurring on the DH fan during flows twenty-five and fifty-two. The avulsion cycles on the ULAcdS fan were more symmetrical (twenty-six and twenty-three flows) than on the DH fan (fifteen and twenty-seven flows).

Despite these differences, the morphometry generated on the ULAcdS fan is extremely similar to that of the DH fan. Avulsion cycles on both fans were defined by periods of channelization where strong lateral levees propagated flows over increasingly long distances where they were punctuated by distinct depositional end lobes. Both fans experienced extended phases of channel backfilling where deposit end lobes migrated upstream. This process completely buried once-active channels, leaving a convex topographic feature in its place. Phases of unchannelized flow were also exhibited on both fans, however, the first phase of unchannelized flow evident on the ULAcdS fan differed from the second. The first phase resembled those that occurred on the DH fan where deposits were short and wide, depositing material on either side of the fan. The second phase preceded the second avulsion and while the flows were still clearly unchannelized, deposition only occurred on one side of the fan. The main difference between the ULAcdS fan and the DH fan, however, involves the processes whereby the fans evolve. This difference is reviewed in detail in the following section.

Evolution of alluvial fans with limited accommodation space

The overarching hypothesis guiding this research is that frequent fan-toe removal on autogenically controlled debris-flow fans results in superelevation of the active fan segment which leads to shifts in the locus of deposition. The results from two small-scale physical modeling experiments do not support this hypothesis, and thus it is rejected. Rather, the creation of the experimental fans reveals an alternative process that promotes fan avulsion. The limited accommodation space fan generated in these experiments evolves through cycles of channelization, formation of a stabilized channel in the center of the fan, channel narrowing and overflow, and avulsion.

Channelization occurs as a result of the formation of coarse-grained lateral levees, a process that is well documented in the generation of the unlimited accommodation space fan as well as in experiments by De Haas et al., 2016. Once channelization is established, a stabilized channel forms in the center of the fan and persists through the length of the experiment. This stable channel is inferred to occur in response to a combination of two factors. First, through a feedback mechanism whereby in-channel accretion occurs more rapidly in the apex to mid-fan regions, resulting in a dramatic increase in slope in the distal region of the fan. As slope increases in the distal region, less in-channel accretion occurs and the channel is stabilized. Second, through an absence of channel backfilling. Backfilling of the active channel does not occur on the limited accommodation space fan because the debris that would form the depositional end lobes that backfill the channel, as on the unlimited accommodation space fan, are consistently removed by the simulated fan-toe erosion.

Following channel stabilization, the active channel progressively narrows until one of the lateral levees is breached and avulsion is initiated. An increasing volume of debris is directed toward the breach path until this new path is channelized. At this point in the autogenic avulsion process, two flow-paths are active as the stabilized channel is maintained and a newer, secondary channel is established following avulsion. Continuing the autogenic avulsion cycle, the secondary channel migrates toward the center of the fan. During this time period, the secondary channel begins to narrow as it is bounded by a medially migrating levee on one side and antecedent topography (stabilized channel) on the other. Over time, the secondary and stabilized channels begin to merge into one flow path until the channel progressively narrows and one of the lateral levees is breached and the process begins again.

Future research

The research presented in this thesis, with particular reference to the second experimental fan, reflects a very simplified model of conditions that are observed in the natural environment. In reality, the mobile and dynamic nature of river systems frequently creates an asymmetrical pattern in fan-toe erosion. While the static nature of the simulated boundary imposed on the experimental fan provides an important basis for beginning to understand how limited accommodation space affects debris-flow fan development, future work is encouraged to move toward an experimental design that better reflects the migratory nature of the trunk channels limiting natural fan development.

Further research may involve simulating different kinds of limitations on accommodation space. For example, lateral limitations as in bajada systems; distal limitation where debris is not eroded, ex., extremely narrow valleys; or variations in cutoff distances.

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