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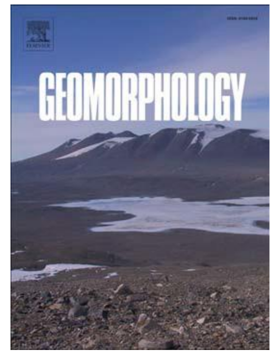

Experimental alluvial fans: advances in understanding of fan dynamics and processes

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Experimental alluvial fans: advances in understanding of fan dynamics and processes

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Abstract

Alluvial fans are depositional systems that develop because of a disparity between the upstream and downstream sediment transport capacity of a system, usually at the base of mountain fronts as rivers emerge from the constrained mountain area onto the plain. They are dynamic landforms that are prone to abrupt changes on a geomorphological (decades to centuries) time scale, whilst also being long-term deposition features that preserve sedimentary strata and are sensitive indictors of environmental change. The complexity of interactions between catchment characteristics, climate, tectonics, internal system feedbacks, and environmental processes on field alluvial fans means that it is difficult to isolate individual variables in a field setting; therefore, the controlled conditions afforded by experimental models has provided a novel technique to overcome some of these complexities. The use of experimental models of alluvial fans has a long history and these have been implemented over a range of different research areas utilising various experimental designs. Using this technique, important advances have been made in determining the primary factors influencing fan slope, understanding of avulsion dynamics, identifying autogenic processes driving change on fan systems independent of any change in external conditions, and the mechanics of flow and flood risk on alluvial fans, to name a few. However, experiments cannot be carried out in isolation. Thus, combining the findings from experimental alluvial fans with field research and numerical modelling is important and, likewise, using these techniques to inform experimental design. If this can be achieved, there is potential for future experimental developments to explore key alluvial fan issues such as stratigraphic preservation potential and simulating extra terrestrial fan systems.

Keywords: alluvial fan; fluvial fan; experiment; physical model; allogenic; autogenic; flow processes; morphology

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1. Introduction

Experimental models have been used in alluvial fan research for over 50 years, with experiments covering aspects of alluvial fan morphology and dynamics in areas such as flow process understanding, flood hazard simulation, sequence stratigraphy, and identifying autogenic signals. These have demonstrated a general experience that the tendencies observed in small-scale experimental fans are relevant to field-scale trends (Davies et al., 2003) and, more recently, have been used to parameterise and verify numerical models. The controlled conditions afforded by experiments allow isolation of individual variables and processes that would not be possible through field monitoring alone.

Alluvial fans are sedimentary deposits formed at the base of mountain fronts as rivers emerge out of the mountain range (Bull, 1977; Fig. 1) or at the river mouth where it flows into a large valley or water body. Spreading their loads in a radiating pattern from a single apex, alluvial fans form conical bodies typically with slightly concave long profiles and convex cross-profiles (Clevis et al., 2003). In fluvial systems, alluvial fans can act as important controls on sediment transfer, acting as an interface between the sediment production areas of the upland catchments and the transitory and depositional lowland regions. They therefore provide a valuable record of environmental change. Blair and McPherson (1994) classified alluvial fan styles based on process combinations; they surmised that alluvial fans can be divided into two main categories on the basis of their dominant primary processes and resultant mechanical behaviour: fluvially formed fans, composed from sediment moved by the force of water; and debris-flow fans, in which sediment is transported by gravity acting directly on the materials. Fluvial-formed fans tend to be larger with lower gradients, while debris-flow fans are smaller in size and steeper. This paper will specifically focus on experiments related to fluvial-formed fans.

FIGURE 1

Alluvial fans have a global distribution and form in a diverse range of climatic and tectonic regimes. In all climatic environments, alluvial fans represent critical sites of sediment routing in mountainous watersheds and may play an important buffering role in mountain geomorphic or sediment systems. They trap the bulk of the coarse sediment delivered from the mountain catchment, and therefore affect the sediment dynamics

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downstream, either in relation to distal fluvial systems or to sedimentary basin environments (Harvey, 2005). Alluvial fans represent small-scale coupled transport/depositional systems and therefore provide the ideal opportunity to explore the relationships between the dominant surface processes, sediment transport, and morphology. The constant reworking of alluvial fans at geomorphological time scales (decades to centuries in duration) combined with the dynamic response of alluvial fans to changing input conditions and the resulting, often abrupt, change in flow conditions has led to investigation into the hazard posed by alluvial fans and attempting to predict flow paths for engineering purposes (e.g., FEMA, 2000, 2003).

Understanding alluvial fan response and evolution requires knowledge of the alluvial fan morphology, the processes operating on the fans, and how these alter in different spatial and temporal settings. These are dependent on allogenic (forces external to the fan system such as catchment characteristics, tectonics, climate, and base-level change) and autogenic (internally derived thresholds within the fan system) controls. Complex interaction of these forcings occur as an alluvial fan evolves and, the often chaotic preservation of stratigraphic sequences, makes it difficult to isolate individual impacts of one from the other in a field setting. The ability to control boundary and input conditions, as well as the ease of monitoring surface conditions and topography offered by experimental work, can provide an ideal solution. Despite the long history of research into alluvial fans it was not until the 1960s that this changed from a study of the landform itself to attempts to understand the significance of process-form relationships (Blissenbach, 1964; Bull, 1964, 1977; Denny, 1965, 1967; Hooke, 1967, 1968). From these early studies, the importance of using experimental modelling to isolate complex variables during alluvial fan evolution was emphasised, and it started a strong tradition of physical modelling in alluvial fan research. The aim of this paper is to review how experimental work has led to the development of theory and process understanding on alluvial fans, explore the variety of experiments that have been undertaken, and to assess how these findings have influenced field and numerical modelling studies, as well as think to the future of experimental work in alluvial fan research.

2. A history of experimental work on alluvial fans

2.1. The pioneers

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Experimental studies of alluvial fans date back to the 1960s with the work of Roger Hooke (Hooke, 1967, 1968; Hooke and Rohrer, 1979). These early investigations examined fan morphology and explored the different mechanisms of sediment transport on the fan comparing fans created in a laboratory environment with examples from Death Valley, California. Although the findings from these experimental fans were compared to natural alluvial fans, they were not scale models of a specific prototype but instead used a *similarity of processes* analogue approach − experimental fans were therefore treated as systems unto themselves and not scale models or analogues. The success of analogue modelling is based on the theory that important aspects of morphodynamics are scale independent over a wide range of scale, thus one uses the self-similarity produced by these experiments to observe and investigate processes and causes of change (Paola et al., 2009). Hooke (1968) concluded that the slope of an alluvial fan is determined by the grain size, depositional processes, and water discharge; as larger fans are associated with larger drainage basins and hence larger discharges than smaller fans, the fan slope generally decreases with increasing fan area. The location of the intersection point (the location where the entrenched channel attains the fan surface and flow diverges into multiple channels, as defined by Schumm et al., 1987) on the alluvial fan significantly affects the locus of sediment deposition, and it was also suggested that fan head channel entrenchment may be an autogenic feedback resulting from flow configurations on the fan surface. Even under constant conditions transient trenches were still observed to develop; the channel often switched from a relatively low slope to a steeper slope, and this was often accompanied by channel incision at the fan head (Hooke, 1967).

Another early proponent of experimental work on alluvial fans was Stanley Schumm, who also used an analogue modelling approach. This work demonstrated that alluvial fans constructed in the laboratory at a small scale exhibited many of the fundamental features and processes that you would expect to find on natural alluvial fans, including depositional sheetflow (defined as over 50% of the fan area covered by distributed flows), channelization of flow, lateral migration, avulsions (abrupt channel relocation), and channel entrenchment (Schumm, 1977; Schumm et al., 1987; Fig. 2). These experiments also concluded that the growth of experimental alluvial fans was dominated by repeated fan head trenching and that the flow conditions at the apex were important factors in determining the areal extent of flowing water and sediment, with fan head incision being controlled by an internal slope-related stability threshold across which a change in channel form occurred. A consequence of this, at least in this experimental situation, was that fan

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morphology was a more important control on flow behaviour than the external variation of sediment input (Schumm et al., 1987).

FIGURE 2

The analogue nature of Hooke (1967) and Schumm‟s (1977) experiments meant that no attempt was made to quantify alluvial fan changes and refer these directly to alluvial fans in the field, but instead they formed a body of basic observations on fan form and associated process response to aid field researchers when interpreting sequence stratigraphy and geomorphological processes. The work of Hooke and Schumm was fundamental in the development of future experimental work into alluvial fans, and led to a resurgence in this technique in the 1990s.

2.2. The impact of allogenic factors

Alluvial fans are sensitive to changes in their input conditions and in particular the relationship between the sediment and water supply onto the fan system. The relationship between water discharge and sediment supply rate in controlling fan slope was explored by Guerit et al. (2014) using a microscale model; a mixture of water and glycerol was used to move glass beads and create a small-scale one-dimensional fan < 1 m in length. The Reynolds number was scaled to ensure laminar flow. These experiments showed that the water discharge controls the geometry of the fan by setting the fan slope near its critical value, while the sediment supply to the fan determines the velocity at which the fan grows. Therefore, we can see that the relationship between water discharge and sediment supply onto fans is important in determining the fan morphology, highlighting the need to understand the impact of allogenic factors (such as base level, tectonic, and climate changes) that control the spatial and temporal distribution of input conditions and also the accommodation space available for fan growth. Hooke and Dorn (1992) used Froude-scale modelling to determine the allogenic controls on alluvial fans in Death Valley, California. In Froude-scale models the flow Reynolds number is relaxed while remaining in the fully turbulent flow regime, but the Froude number is scaled correctly to achieve geometric, kinematic, and dynamic similarity between the model and prototype (Peakall et al., 1996) − in contrast to analogue models, this means that Froude-scale models are scaled to individual field prototypes. This experimental work was used to increase understanding of the entrenchment and

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segmentation occurring on these fans; as this work was being used to investigate the environmental history of a specific set of alluvial fans, the analogue approach previously used by Hooke (1967) was not appropriate and Froude-scaling was used to allow direct comparison between the field fans and experimental results. The incision of valleys and subsequent surface abandonment on a fan surface was found to be related to the level of erosive activity associated with discharge levels, which in turn correlated to the climatic regime. Hooke and Dorn (1992) concluded that the initial entrenchment and segmentation in Death Valley was triggered by loading of the valley with water in a period of wetter climate, a finding that would not have been possible without the improved understanding of process relationships provided by the experimental work − an example of how experimental work can be used to aid field interpretation to eliminate competing hypotheses.

Problems with stratigraphic sequence preservation in the field make it difficult to find pristine stratigraphy that provides a complete record for interpretation of environmental change in any given location. Experimental alluvial fans therefore provide a novel environment to explore and quantify linkages between surface processes and subsurface architecture, providing a view of stratigraphic accumulation unavailable from the field (Martin et al., 2009).

A series of analogue experiments were performed at the Experimental EarthScape (XES) facility at the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota that explored stratigraphic deposition and preservation. The XES basin allows experimental formation of physical stratigraphy in a system with a flexible subsiding floor, enabling the formation of stratigraphy under controlled conditions of base-level change, subsidence, sediment supply, and transport (Paola et al., 2001). Research examining the effects of subsidence rates on fluvial basins using XES (Paola et al., 2001; Sheets et al., 2002; Hickson et al., 2005; Martin et al., 2009) demonstrated that experiments are a useful tool for investigating stratigraphic assembly and for understanding how complex stratigraphy may arise from simple events, allowing the study of depositional mechanics across the spectrum of time scales from individual events to the filling of a basin (Sheets et al., 2002), and the results were comparable to stratigraphy found in the field. The bulk of alluvial deposition was accomplished by short-lived flows, and established channels were found to act largely as conduits for sediment, with overbank spills and flow expansions depositing a disproportionate amount of sediment. Sheets et al. (2002) also proposed the „stratigraphic integral scale‟, a consistent scale that

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measured the time required to average individual depositional events into large-scale stratal patterns in the experiments presented this was found to be equal to the time necessary for deposition of several scour depths worth of sediment at the average aggradation rate. Martin et al. (2009) also noted varying levels of preservation during the experiments, with stacking arrangement closely associated with depositional history and mass-balance and a critical distinguishing feature of an allogenic episode was the greater lateral persistence of the discordance recorded in the stratigraphy. Although this work was focused on fluvial basins rather than specifically on alluvial fans, the results had implications for research on alluvial fan stratigraphy, and from an experimental perspective it proved the usefulness of experimental modelling for exploring stratigraphy and thus opening up potential new research directions for experimental alluvial fans.

Research in the Delta basin at Tulane University's (Louisiana, USA) Sediment Dynamics Laboratory investigated the completeness of stratigraphic record preservation on experimental alluvial fans and deltas (Straub and Esposito, 2013; Straub and Wang, 2013; Fig. 3). The experimental fans produced had ponded water at the toe and are therefore classified as fan deltas, but parallels were drawn with alluvial fans. Subject to gradual base-level rise, the experiments demonstrated that environmental signals disconnected from a sediment routing system are best preserved in systems with low surface roughness. Two time scales were proposed by Straub and Esposito (2013) to explain the stratigraphic completeness: the amount of time necessary to generate a deposit to explore topography changes, and the rate of net deposition characterised by the mobility of the channel on the delta tops. They also suggested that stratigraphic completeness in deltaic settings is controlled by the balance of aggradation and lateral channel migrations, with rapid aggradation relative to lateral channel migration leading to high stratigraphic completeness, whereas rapid lateral migration of deep channels relative to system aggradation results in frequent deposit reworking (Straub and Esposito, 2013, p. 12). Straub and Wang (2013) also found that the degree of organization (i.e., the lack of noise in autogenic signals) in basin-fill patterns increases with the ratio of sediment supply to water discharge; this finding suggests that stratigraphy constructed by alluvial fans (typically characterised by a low sediment-to-water ratio) will have less organization than a fan delta that has a higher sediment-to-water ratio.

FIGURE 3

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Many basic sequence concepts appear to be independent of scale and process detail (Martin et al., 2009), demonstrating similarity between the field and experimental model in generating stratigraphic sequences, thus providing an opportunity for experimental work to simulate sequences from a range of processes to aid in the understanding of field stratigraphic interpretation. The research to date that has been undertaken on fluvial basins is applicable to alluvial fan environments, but specific fan experiments exploring stratigraphic patterns and preservation would be valuable to inform a large section of the alluvial fan research community and determine what, if any, variations were found between fans and other fluvial basins.

2.3. Flow processes and avulsions

The early alluvial fan experimental work (Hooke, 1968; Hooke and Rohrer 1979; Schumm et al. 1987) observed variations in flow processes and found that under conditions of constant water and sediment supply the fan intersection point migrated across the fan surface, with repeated fan head trenching as a result of over steepening on the fan surface. These changes in flow condition were driven by feedbacks intrinsic to the fan system, and there has been growing recognition by alluvial fan researchers of the importance of these internal processes or autogenic factors in driving change on alluvial fans. The term *autogenic* is used to describe the process response arising from internal feedbacks with the fan system independent of alterations in the allogenic (external) controls (Muto et al., 2007). However, the role of autogenic processes in alluvial fans remains poorly constrained: the sporadic occurrence of effective geomorphic events in present-day alluvial fans renders the direct observation of processes unlikely, and the chaotic architecture of ancient fan successions has hampered detailed stratigraphic analysis (Ventra and Nichols, 2014). By enabling control of the external factors influencing fan systems, experimental modelling has therefore provided an avenue to explore the influence of autogenic processes on flow patterns and the resultant morphology.

In 1998 a series of papers (Parker et al., 1998a, b; Whipple et al., 1998) were published from SAFL exploring the surface processes operating on alluvial fans using a combination of physical and numerical modelling based on a field case of an alluvial fan in a tailing basin of an iron mine; these papers proved to be fundamental in exploring the importance of autogenic factors in driving change on alluvial fans. The experimental work was presented in Whipple et al. (1998); this aimed to quantify the relationship between

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fan morphology, flow channelization, and boundary conditions (such as sediment and water discharge and grain size) under constant input conditions (sediment supply and water discharge) and steady subsidence rates. Despite the constant input conditions flow varied in space and time between expanding sheetflow and channelized braiding flow. The authors did note that the necessity to treat the flows on model fans as sheetflow rather than channelized flows may be in part a scale effect, if either the fan width or length is not sufficiently large compared to the channel dimensions (Whipple et al., 1998); however, the differentiation between the two phases of flow was apparent and, to be more applicable to field situations, could be summarised as fully channelized flow and multi-channel unstable flow conditions during sheetflow in the experiments. The degree of flow channelisation had an important influence of sedimentation patterns, dynamics, and the resulting depositional slope; and the extent to which flow channelized was found to be dependent on water discharge and grain size but independent of sediment supply. The results from these papers (Parker et al., 1998a, b; Whipple et al., 1998) demonstrated substantial difference between the equilibrium profiles of fans generated by sheetflow and channelized flow, and they highlighted the importance incorporating the range of flow processes in the theoretical understanding of fan development.

Experimental work on alluvial fans and fan deltas at the Eurotank flume facility, Utrecht University in the Netherlands (van Dijk et al., 2008, 2009), used an analogue modelling approach to investigate the influence of autogenic processes on flow processes on fans; this work demonstrated that in the absence of variations in tectonics and sea-level change and with constant sediment and water inputs, autogenic variability formed alternating cycles of sheetflow and channelized flow related to a critical slope threshold (Fig. 4). Initially, sheetflow over the fan surface induced deposition, increasing fan slope and curvature to a point where surface geometry was susceptible to channelisation instability. Once channelized flow dominates, incision begins and the fan surface is degraded to a lower slope, this releases a pulse of sediment that pushes the fan toe forward (i.e. fan growth). Sheetflow resumes once the surface has regraded and the cycle repeats in a periodic fashion (van Dijk et al., 2009; Fig. 4). Hamilton et al. (2013) also simulated autogenic incision-backfilling cycles on experimental alluvial fans, similar cycles of sheetflow and channelized flow where observed, with the latter being associated with a period of flow expansion in the fan toe area and creation of a lobe deposit enabling fan propagation; whereas during the sheetflow periods the fan aggraded and steepened. The initialization of channelized flow corresponded to a critical slope being exceeded similar to

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the findings of van Dijk et al. (2008, 2009). These autogenic cycles of aggrading sheetflow alternating with incisional channelized flow have also been simulated on experiments of fan deltas (e.g., Kim and Muto, 2007; Kim and Paola, 2007; Kim and Jerolmack, 2008; Hoyal and Sheets, 2009; van Dijk et al., 2009, 2012); however, van Dijk et al. (2012) found that although the observed cycles were similar between the two landforms, the impact of ponded water at the toe of the fan delta created backwater effects that reduced the frequency of channelized phases and made these more regular on fan deltas than terrestrial alluvial fans.

FIGURE 4

The importance of downstream boundary impacts on alluvial fan response was highlighted by a series of experimental fans carried out by Clarke et al. (2010) at the University of Exeter Sediment Research Facility in the UK. Using an analogue physical model, alluvial fan growth was restricted laterally to 90º and longitudinally through the imposition of a downstream boundary condition in the form of a drainage channel that was cleared to sediment, to replicate laterally confined alluvial fans that experience toe-trimming − a common occurrence in natural systems where mountain tributary fans are coupled to a larger trunk channel in the main valley floor (see Fig. 1B for a field example of this). In experiments with a constant water discharge and sediment supply rate, a transition was observed from sheetflow dominated in the early stages of the experiment, through a period of multiple channels that rapidly migrated, into a lateral migration of 1-3 main channels, with all experiments progressing to the formation of a single incising channel. Observed flow widths were calculated as a function of distance downfan and highlighted the transition of flow processes (shown in Fig. 5A), with flow width reducing with time through the experiment reflecting the reduction of flow on the fan surface with the formation of a single incising channel (Clarke et al., 2010; Nicholas et al., 2009; and shown in Fig. 5B). The limit on accommodation space caused by downstream boundary conditions removed the autogenic cycles that have been found in other alluvial fan experiments (van Dijk et al., 2008, 2009, 2012; Hamilton et al., 2013) and forced the flow to remain channelised once incision has begun. Once the fan extent reached the downstream boundary, the channel backfilling (observed in the early stages of the experiments) ceased as the incised channel came to grade with the new and now fixed base level; the feedback mechanism (observed by van Dijk et al., 2008, 2009; Hamilton et al., 2013) that led to flow deceleration and subsequent backfilling was eliminated, thus preventing the re initiation of sheetflow

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conditions on the fan. Exploring the impact of boundary conditions on the autogenic response of alluvial fans, van Dijk et al. (2012) proposed that the morphodynamics of alluvial fans are determined primarily by upstream boundary conditions, with apex conditions and upper fan slope driving avulsions and channel location. However, downstream boundary conditions can propagate upfan and influence the flow processes occurring on the entire fan surface, demonstrated by the complete restriction of autogenic cycles caused by the imposition of a drainage channel at the toe of the experimental fans shown by Clarke et al. (2010), and must therefore also be considered.

FIGURE 5

Understanding the long-term occurrence, behaviour, and triggers of avulsions on alluvial fans has long eluded researchers; and experiments have been used to document the mechanisms of avulsion over the course of an experimental run. Bryant et al. (1995) used an analogue physical model to measure avulsion frequency as a function of sediment feed rate on a series of small-scale experimental fluvial fans. An avulsion in this investigation was defined as a newly created channel that carried at least 50% of the discharge from the old channel. Sediment flux increased, the avulsion rate first increased and then stabilized as mass flows began to influence deposition, and the experiments also showed that less total sediment volume was needed to trigger an avulsion as the sediment supply rate increased. This is in contrast to the findings of Ashworth et al. (2004, 2006) who used Froude-scale modelling to observe avulsions in braided rivers and found that avulsion frequency increased with sediment supply but at a rate slower than the increase in the sediment feed rate. Ashworth et al. (2004) concluded that the most probable cause of this difference was the dependency of sediment supply and avulsion frequency on bed slope; the steeper fan slopes of Bryant et al. (1995) created multi-channel systems that are inherently less stable. The probability of avulsion is therefore likely to be greater with a smaller change in sediment supply, leading to the conclusion that alluvial fans are more prone to avulsion events than river systems.

A series of experiments simulating conditions of steep alluvial fans to isolate the dynamics of the avulsion process during fan evolution were run at the University of Pennsylvania (Reitz et al., 2010). These found that avulsions followed a regular cyclic pattern, which consisted of the following stages: (i) flow abruptly

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collapses into a single channel, focusing rapid deposition at the channel mouth; (ii) progradation causes a decrease in slope until the channel can no longer transport the supplied load; (iii) within-channel deposition drives backfilling from the fan margin toward the apex; and (iv) produces a brief *finding phase* (i.e., a myriad of potential flow paths are filled with water) (Reitz et al., 2010, p. 1). The cycle ends when a new path is selected and the process begins again (see Fig. 6). In agreement with Bryant et al. (1995), avulsion frequency increased with deposition rate, and was principally determined by the ratio of bed deposition rate to channel depth. Dynamic similarity was found between experimental fans and those in the field using a calculated avulsion period, with comparisons being drawn between the experimental findings and the Kosi River fan in India. Continuation of this work displayed a tendency for flow to reoccupy former channels paths, even when these have been backfilled, and that the avulsion time scale increases with time for a prograding fan and decreases with sediment feed rate (Reitz and Jerolmack, 2012). In contrast, Hamilton et al. (2013) ran a series of supercritical (i.e., a Froude number > 1) experimental fans and found that no discernible preferential flow paths formed, therefore resulting in little channel reoccupation, indicating less fan memory than Reitz and Jerolmack (2012). Hamilton et al. (2013) surmised that this difference was caused by the subcritical nature of Reitz and Jerolmack's (2012) experimental fans compared to the supercritical fans created by Hamilton et al. (2013). Supercritical backfilling leaves very little channel imprint on the fan surface, thus reducing future reoccupation, and therefore emphasising the need to consider flow conditions on the fan surface when examining avulsion dynamics on an alluvial fan.

FIGURE 6

Alluvial fans are dynamic landforms, the evolution of which is controlled by allogenic forcing and autogenic process-form feedbacks that drive fan change. Disentangling the effects of these two controls is often problematic in field settings where records of past environmental change are fragmentary and understanding of geomorphic processes incomplete. The use of experimental alluvial fan models has enabled examination of the intrinsic changes that occur over the course of fan evolution independent of changes in the autogenic conditions, which has provided insight into the relative dominance of sheetflow and channelized flow processes and the thresholds associated with each. Likewise, the unknown time scale and periodic nature of avulsions and flow regime changes on alluvial fans in the field makes it difficult to monitor landform

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processes prior to, during, and following an event to determine the avulsion mechanics operating. The use of experimental modelling has enabled detailed analysis of the processes and morphology surrounding an avulsion event to improve understanding of the triggers and system response to these events.

2.4. Flood hazard

Alluvial fans are often developed areas with urban settlements and transport links across the fan surface; the episodic and, sometimes abrupt, nature of change that can occur on them means that they are often perceived as vulnerable to hazards, especially in regard to flow changes and flood risk. To determine the relationship between fan morphology and flood hazard assessment on an alluvial fan, Zarn (1989; Zarn and Davies, 1994) used an analogue model to investigate aggradation and channel migration on experimental alluvial fans, factors which influence the short-term flood risk at a particular fan location. In the experiments, channel entrenchment and aggradation were observed, related to interception point retreat headward and channel migration caused by concave bank erosion. Zarn and Davies (1994) found the short-term flood risk at any point on the fan surface to be a function of the absolute location of that point, its location relative to the channel position, and the shape of the alluvial fan. The frequency of flow events was found to decrease with increased distance from the fan apex related to the three-dimensional shape of the fan, reduced flow intensity, and altitude with distance downfan. This work emphasised the importance of recognising channel-building processes and fan morphology, as well as the flow conditions, in the formulation of flood-risk maps on alluvial fans. The experimental work for this investigation was carried out at Lincoln University in New Zealand and led to a series of postgraduate theses continuing the experimental work into the flow behaviour of fans under flood conditions (e.g., Straight, 1992; Clarkson, 1999), the findings of which were used to formulate a tentative flood-risk map that could be applied to the surface of alluvial fans. This was determined by knowledge of the recent history of the channel location and prior channel behaviour; the event magnitude and/or the presence of debris flow activity was also not accounted for. The success in applying this map in reality is therefore debatable, given the complexity on natural fans (compared to the experimental conditions used) and the ability to reconstruct the history of morphological change on the fan in sufficient detail for each fan of interest.

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Froude-scale micro-models were also developed to explore fan head aggradation and flood risk on the Waiho alluvial fan on the South Island of New Zealand (Cole, 2001; Davies and McSaveney, 2001; Jolly, 2001; Davies et al., 2003), an area that has a long history of stopbank construction that has impacted on the natural processes occurring on the fan. Using this modelling approach, the aim is to scale the dimensionless variable. However, the small size of the model means that scaling relations are of a large order of magnitude and that some aspects of dynamic similarity have to be sacrificed for the convenience of scale and therefore does not meet the rough-turbulent flow in Froude-scale models at 1:50 or larger scale (Young and Warburton, 1996). The results generated from micro-scale models have to be treated with caution, and the findings are often used to improve qualitative process understanding, similar to an analogue model. A series of experimental investigations were carried out with a 1:3333 scale rough-turbulent hydraulic model of the Waiho alluvial fan proximal region. The natural boundary conditions were altered to simulate the presence of stopbanks; and fan head aggradation was observed in a spatial pattern similar to that recorded in the field, leading to the conclusion that aggradation in this area resulted from the lateral restriction caused by the stopbanks. The findings led to the construction and monitoring of flood protection works along the edge of the alluvial fan to safeguard the nearby community. However, the authors acknowledge that although dynamic similarity was achieved through the presence of rough-turbulent flow, some uncertainty in the similarity achieved between the model and prototype were experienced given the limited prototype calibration data available for model calibration. Despite the uncertainties around micro-scale modelling and the low level of dynamic similarity, Davies et al. (2003) suggested that these could still be used to make reliable quantitative predictions of the effects of engineering works on alluvial fans. The same technique of micro-scale modelling was used by Davies and Korup (2007) to test the hypothesis that in mountainous catchment-fan systems persistent alluvial fan aggradation and trenching may result from infrequent, large, sediment inputs. The Poerua alluvial fan, again in the South Island of New Zealand, experienced a landslide dam burst and subsequent catastrophic flood event in 1999. Prior to this event the Poerua River had been actively incising into the alluvial fan by several metres for over a century; however, the excess sediment from the landslide dam failure resulted in aggradation and an elevated channel surface. The use of micro-scale modelling meant that limited quantitative comparisons could be made between the model and field other than planform geometry and tentatively the Froude number, but these gave support to their hypothesis that fanhead morphology is shaped by occasional large, sediment inputs and demonstrated that the existence of a fanhead trench does not

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guarantee that the fanhead is inactive and therefore safe from aggradation − landslide-induced trenched fanheads are vulnerable to inundation and aggradation at any time from upstream sediment inputs.

Cazanacli et al. (2002) used a Froude-scale experimental model at SAFL to examine flood hazard on alluvial fans through examination of the importance of lateral flow mobility in assessing long-term flood risk of arid zone alluvial fans. Flood risk assessment by agencies such as the Federal Emergency Management Agency (FEMA) in the U.S. tended to estimate the extent of one single large flood event, whereas Cazanacli et al. (2002) used the probability that any initially dry point on the fan will be inundated in a given amount of time that can range from very short to very long intervals. Avulsions were found to occur primarily in the upper fan region but also influenced the flow distribution downfan. Over long time periods (thousands of years at the experimental scale), the distribution of surface flow was found to be relatively uniform but over shorter time periods, flow tended to concentrate in specific areas with others only sporadically flooded (Cazanacli et al., 2002). Estimating the probability of an area flooding was found to be proportional to the cross-sectional area of the flow and inversely proportional to sediment supply, and the area most likely to flood are those areas affected by recent floods. This highlighted the importance of lateral flow mobility, which was found to be at least as important as flood extent in determining the areas of a fan that are at risk from flooding.

3. What has alluvial fan research gained from experimental models?

Experimental models have a long history in alluvial fan research. This paper has outlined the different experimental approaches that have been used to improve understanding of alluvial fans and reviewed the key findings from this research. A short summary of the key theoretical contributions that experimental modelling enabled in alluvial fan research will now be presented, followed by an evaluation of the impact of scaling relations on the validity of the findings presented and in particular how these can be related to the field setting, and how experimental modelling can be used to answer current research questions that the alluvial fan community are focused on.

Observation of process response on experimental fan systems, in detail over short geomorphological time scales and also with uninterrupted temporal coverage over the entire duration of alluvial fan evolution (i.e., geological timescales), has improved understanding of the processes that operate on alluvial fans, how these

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interact with one another, how they vary through time, and the influence these have on fan morphology. Fan slope was found to be largely dependent on the grain size and water discharge (Hooke, 1968; Whipple et al., 1998; Guerit et al., 2014) and is thus fundamentally influenced by the upstream catchment area. However, local variations in fan slope were found to be controlled by internal fan dynamics and the flow position on the fan surface. The type of flow, subcritical or supercritical, also has an impact not only on the surface flow patterns but also on the backfilling of unoccupied channels (Hamilton et al., 2013), impacting the surface topography and potentially the future positioning (and reoccupation) of channels as they migrate across the fan surface (Reitz et al., 2010; Reitz and Jerolmack, 2012). The impact of a critical slope threshold on channel incision was noted in early experiments (Hooke, 1968; Schumm et al., 1987; Whipple et al., 1998), and then further highlighted by the slope control between sheetflow and channelized flow in autogenic cycles (van Dijk et al., 2008, 2009, 2012; Hamilton et al., 2013), and the initiation of avulsion events (Bryant et al., 1995; Reitz et al., 2010). However, downstream boundary conditions can interfere with the usually dominant upstream processes on alluvial fans and alter the slope threshold values and system response dramatically (Clarke et al., 2010). Experimental modelling of alluvial fans has also had a significant impact on the management of these landforms; simulating flood hazard and potential avulsion paths has enabled better prediction of potential risk areas on the fan surface, leading to incorporation of fan morphology and the legacy of channel occupation into assessment of flood risk on fans (e.g., Cazanacli et al., 2002; Davies et al., 2003).

The advantages of using experimental models for alluvial fan research have been listed throughout the paper; they provide a controlled environment to explore a range of input conditions, enable observation of processes from geomorphic to geologic time scales, allow interpretation of sporadic events (e.g., avulsions) that are difficult to investigate *in situ* and can provide a holistic view of fan system response, to name a few. However, there are drawbacks to their use, and in particular formidable scaling problems that need to be addressed (Peakall et al., 1996; Paola, 2000; Paola et al., 2009). Peakall et al. (1996) suggested that experimental models can be classified by their specificity (degree to which the model replicates a prototype); they may be either one-to-one replicas of the field prototype (not explored in this paper and rarely used in alluvial fan experiments), scaled by Froude number only over a range of spatial scales, or serve as unscaled experimental analogues that attempt to reproduce some properties of the prototype. The order that these

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types of model are listed also represents the loss of model replicability from a specific prototype in the real world. With regard to similarity, three types are important to physical model studies (French, 1987): (i) geometric similarity, where all corresponding dimensions are similar and pertain to similarity in form; (ii) kinematic similarity, where the paths of motion are geometrically similar and ratios of the velocities of the two motions are equal; and (iii) dynamic similarity, where the ratios of the masses and the ratios of the forces involved are equal. In most experimental models, geometric and kinematic similarity can be rather easily achieved; however, complete dynamic similarity is often difficult if not impossible (Yalin, 1971). This is because not all parameters from the field can be accounted and appropriately scaled for within the model; there is no practical way of scaling the forces of gravity, fluid viscosity, and temperature and these will generally be the same for the model and the prototype (detailed discussion of similarity in experimental models is provided in Paola et al., 2009). Thus if the value of an experiment is assessed by how well it equates with a natural system based on classical formal scaling, it may not perform well; but if experiments are instead viewed as tools of analysis, and through comparison of experimental findings with numerical models and field observations, an evaluation can be made of how completely they capture the dynamics of natural systems (Martin et al., 2009), they prove to be very useful. The impact of scaling in experimental models can often distort the dominance of certain morphologies and flow processes, and so care must be taken when interpreting experimental findings in a field setting. For example, scale effects between fan and channel dimensions in an experiment can lead to the regular production of supercritical flows and sheetflow processes on the experimental fans (Whipple et al., 1998; van Dijk et al., 2008, 2009, 2012; Clarke et al., 2010; Hamilton et al., 2013), which are not often observed on field fans. Rather than a direct comparison of the flow processes between field and experimental fans, and trying to identify sheetflow *per se* on field fans, more useful instead is to interpret the flow behaviour, and associated aggradation or incision, and use these as a guide to the environmental conditions or autogenic forcing in a field setting. Ultimately, the aim of the experimental work and availability of field data will determine the scaling approach that is used; however, in considering the role of experimental work in driving understanding of alluvial fans, some consideration of how the findings from experiments can be translated into the field needs to be made. The remainder of this section will explore how experimental models could be used in the future to more effectively bridge this gap between the two techniques and assist in addressing key alluvial fan research areas.

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The use of experimental alluvial fans has provided an important addition to alluvial fan research and verified much of the fundamental theory on fan morphology and flow dynamics. However, there are still many unknowns in this research area, and experimental models are well placed to address some of the key areas that are currently being investigated. In particular, experimental models could lead the way in exploring stratigraphic completeness and preservation on alluvial fans, defining an autogenic signal within the fan system, determining the impact of boundary conditions on fan response, and using experimental fans to simulate extra terrestrial landforms.

Jerolmack and Paola (2010) proposed that transmission of environmental signals are *shredded* by autogenic signals and internal processes influencing sediment transport, with only a certain magnitude of event being preserved intact in the stratigraphic record. This has implications for the interpretation of environmental change from alluvial fan sequences, and a better understanding of the frequency and magnitude of allogenic events that are preserved needs to be developed in controlled experimental conditions and then applied to field areas. Initial experiments have attempted to quantify the magnitude of autogenic dynamics related to allogenic processes on fan deltas (Straub and Esposito, 2013; Straub and Wang, 2013), but wider experiments need to be undertaken to better constrain the *shredding* potential in a range of environmental settings to guide researchers in the field of the magnitude of external forcing that may have been preserved intact in any given environment. Secondly, although a clear autogenic signal has been found on experimental alluvial fans, how to differentiate between this signal and allogenic-driven change in the flow regime on alluvial fans in the field remains unclear. In a contemporary setting where the environmental conditions are known, one could potentially infer when change is deemed autogenic; but when interpreting a stratigraphic profile, this becomes more difficult to know with any certainty and issues of equifinality arise. Equifinality is when a similar landform or landscape may be created by a number of different processes operating at different times, together or individually (Beven, 1996), potentially making it challenging to derive accurate information about the formative events of these features. Therefore, if scaling relations are taken into consideration, experimental models could be used to parameterise autogenic signals and provide a classification for field identification. This is complicated by the impact of boundary conditions on fan response (demonstrated by Clarke et al., 2010, and van Dijk et al., 2012), as each individual alluvial fan in nature will have a unique set of boundary conditions that are influencing the processes operating on the fan.

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Understanding the influence that each of these boundary conditions exert on alluvial fan dynamics is important, and experiments are an ideal technique to explore this. Finally, experiments can be used to simulate the morphology and characteristics of extra terrestrial alluvial fans. Satellite imagery has identified numerous alluvial fans on the surface of Mars (Armitage et al., 2011) and Titan, and analogue experiments could be used to better understand the observed morphology and past surface water flows. A large number of the extra terrestrial alluvial fans observed preserve a surface fluvial record (i.e., stream patterns, meanders) and slope information these can be measured and experiments run to determine the sediment supply and discharge rates, past hydrological conditions, grain size, and other such variables to analyse how extra terrestrial fans compare to those on Earth and to attempt to determine the formative processes. Experimental fan deltas modelled after conditions on Mars have been successful in replicating present day features and have begun to explore the formative events that occurred to produce these landforms (e.g., Kraal et al., 2008; Kleinhans et al., 2010; de Villiers et al., 2013), but there is still potential for significant advances to be made in the understanding of extra terrestrial fans.

4. Conclusions

Experimental modelling provides a range of advantages unavailable to other methods of scientific investigation. Experiments can be used to generate and test hypotheses, or used simply for prediction and description (Schumm et al., 1987). As Paola et al. (2001, p 5) said „*we use theory to link experiments and field cases. Once a theory has had a good workout in a controlled system, we can be more confident about using it to scale the experimental results to the field and to evaluate the effects that cannot be scaled down to experiments'*. The ability to manipulate the boundary and input conditions in a physical model means that experimental fans can be used to gain a conceptual understanding of the fan system that would be difficult to gain in the field. Researchers have often speculated on aspects of fan morphology and patterns of hydrology but, the time scales involved, mean that few have actually observed in the field the processes of deposition and erosion by which a fan is made. The reduced physical size and relatively rapid rate of formation of experimental fans allows collection of spatial and temporal records of fan building over the entire period of fan evolution, with high-resolution monitoring of the topography and flow.

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Experimental models have a long history in alluvial fan research dating back over 50 years. Some of the fundamental alluvial fan theory was initiated and/or verified using experiments, including the relationship between fan size and flow regime and the influence of grain size and discharge on fan slope. The complexity of studying alluvial fans in a field setting − with processes on a geomorphological time scale (decades to centuries) and an often incomplete sequence stratigraphy preserved in the rock record − means that experiments have provided a novel and informative alternative. The resurgence in the use of experimental modelling for alluvial fan research in recent years has provided insight into flow processes and avulsion dynamics, autogenic processes driving change in fan systems, and stratigraphic preservation. This improved understanding from a laboratory setting has been fed into field observation and numerical modelling of alluvial fans to better understand the evolution and response of these systems; however, potential remains to improve the communication between experimental results and the implications of these in a field setting. Looking to the future and the key theoretical unknowns in alluvial fan studies, experimental modelling could play an integral part in exploring the stratigraphic preservation potential. This could be used to strengthen field understanding of process response and how it is recorded in sequences, as well as attempting to quantify the autogenic signal and the impact of boundary conditions on internal process-form feedbacks. Experimental alluvial fans could also be used to improve knowledge of extra terrestrial landforms. Experimental modelling has a bright future in alluvial fan research, and if used in conjunction with other techniques, it can continue to provide new information to better understand these dynamic landforms.

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Fig. 1. (A) Conceptual diagram of an alluvial fan (after Rachocki, 1981); (B) Centre Creek, a fluvial-formed alluvial fan in the South Island of New Zealand (photo by L. Clarke).

Fig. 2. (A) Sheetflow and (B) channelized flow simulated on an experimental alluvial fan (Images from alluvial fan experiments run by the author at the University of Exeter Sediment Research Facility).

Fig. 3. (A) Schematic diagram of Tulane Delta basin facility; (B) (C) and (D) photographs of active delta tops during experimental runs TDB-10-1, TDB-10-2, and TDB-11-1, respectively (taken from Straub and Wang, 2013, p. 627).

Fig. 4. Shaded DEMs of the autogenic sheetflow − channelized incision cycles (taken from van Dijk et al., 2012, p. 2137).

Fig. 5. (A) Conceptual diagram showing the pattern of change in fractional flow width with distance downfan through experimental time based on the experimental results presented in Clarke et al. (2010); (B) photograph showing the single channel incision that occurred at the end of each experimental period.

Fig. 6. Avulsion sequence observed by Reitz and Jerolmack (2012). Images are from successive frames with a time interval of 2 min with the dark areas showing the fan and white representing the movement of water and grains between frames. The system recursively (A) strongly channelizes, (B) pushes out the shoreline, (C) flares out locally to establish a semi circular lobe, (D) backfills, (E) floods, and (F) channelizes in a new location (taken from Reitz and Jerolmack, 2012, p. 8).

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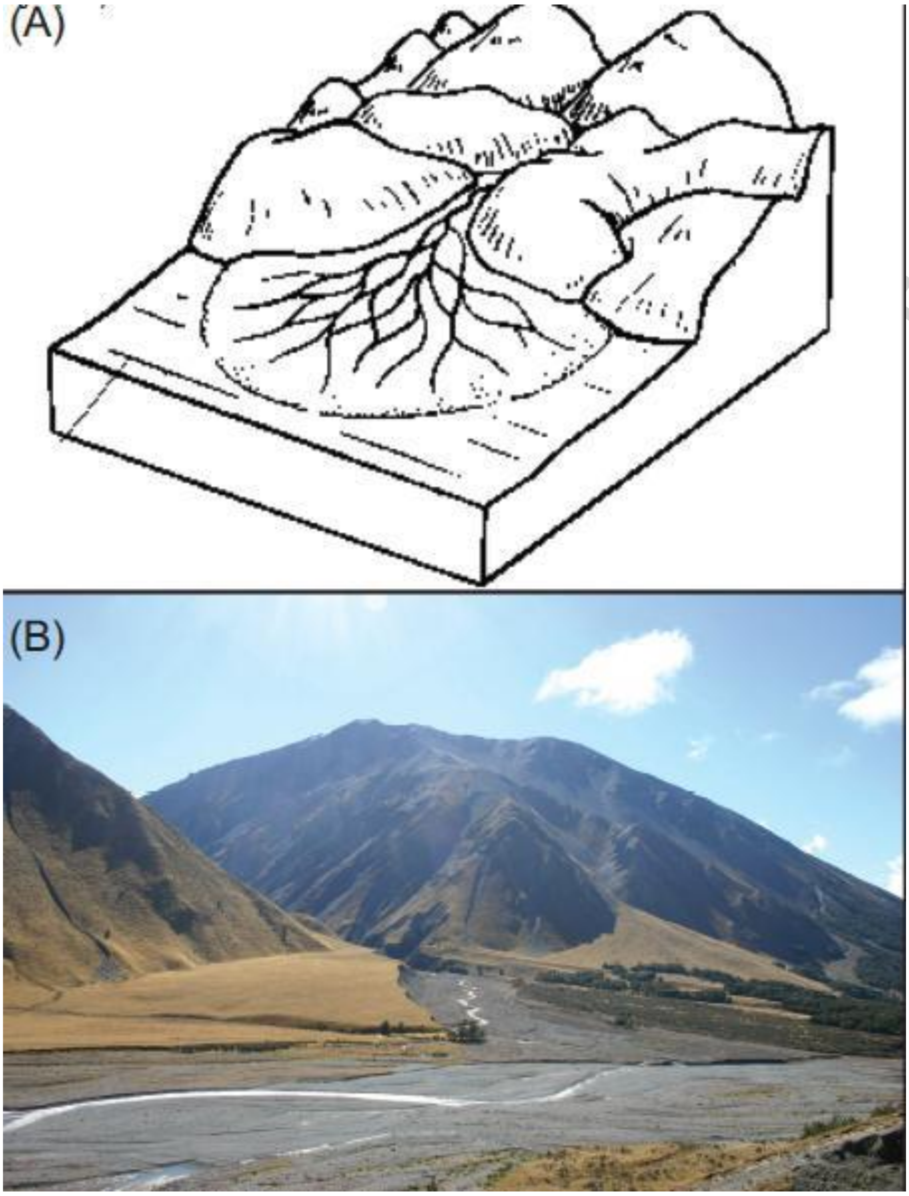

Figure 1

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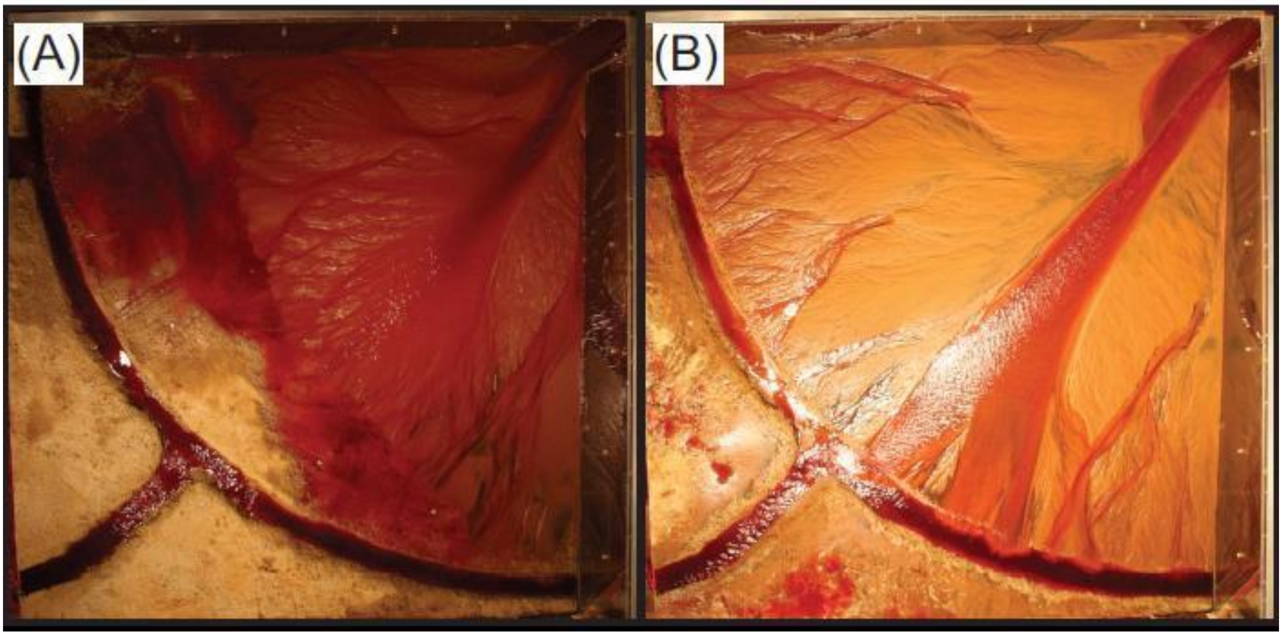

Figure 2

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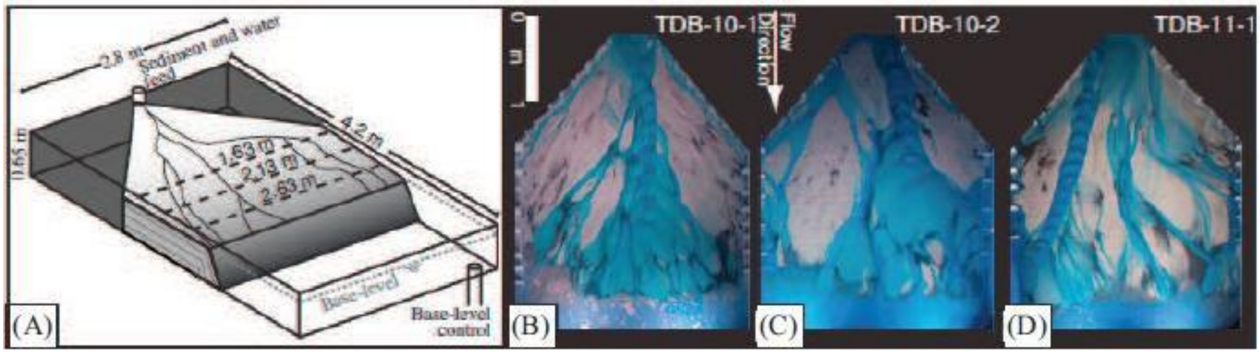

Figure 3

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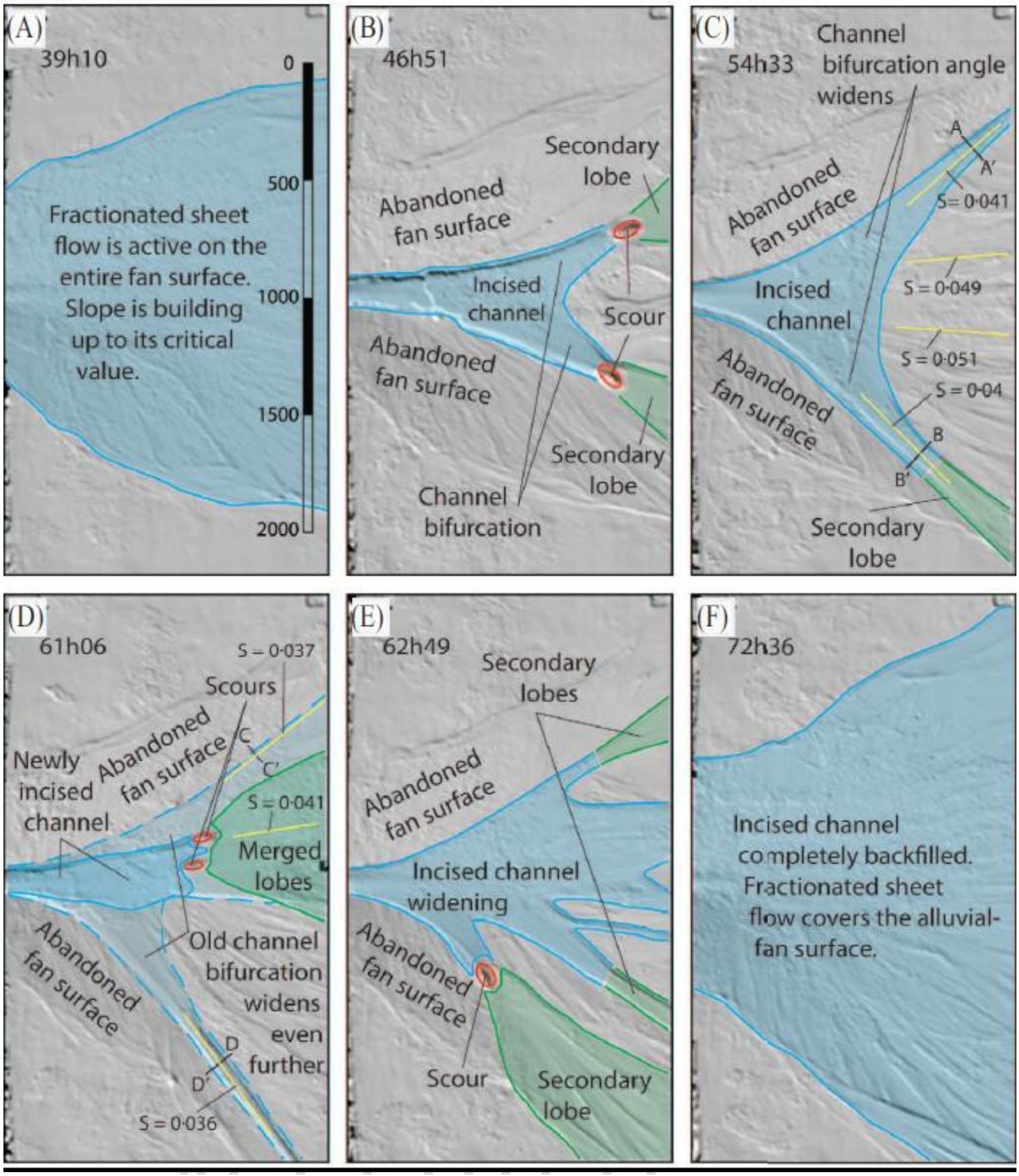
(A)
39h10
0
500
1000
1500
2000
Fractionated sheet flow is active on the entire fan surface. Slope is building up to its critical value.
(B)
46h51
Secondary lobe
Abandoned fan surface
Incised channel
Scour
Abandoned fan surface
Secondary lobe
Channel bifurcation
(C)
54h33
Channel bifurcation angle widens
A
A'
S = 0·041
Abandoned fan surface
Incised channel
S = 0·049
S = 0·051
S = 0·04
Abandoned fan surface
B
B'
Secondary lobe
(D)
61h06
S = 0·037
Scours
Newly incised channel
Abandoned fan surface
C
C'
S = 0·041
Merged lobes
Abandoned fan surface
Old channel bifurcation widens even further
D
D'
S = 0·036
(E)
62h49
Secondary lobes
Abandoned fan surface
Incised channel widening
Abandoned fan surface
Scour
Secondary lobe
(F)
72h36
Incised channel completely backfilled. Fractionated sheet flow covers the alluvial-fan surface.

Figure 4

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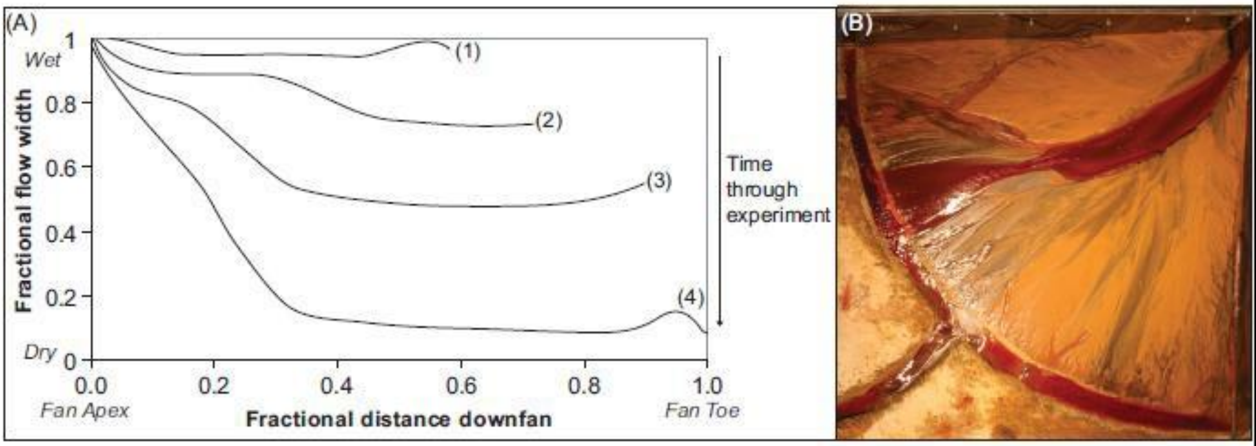

Figure 5

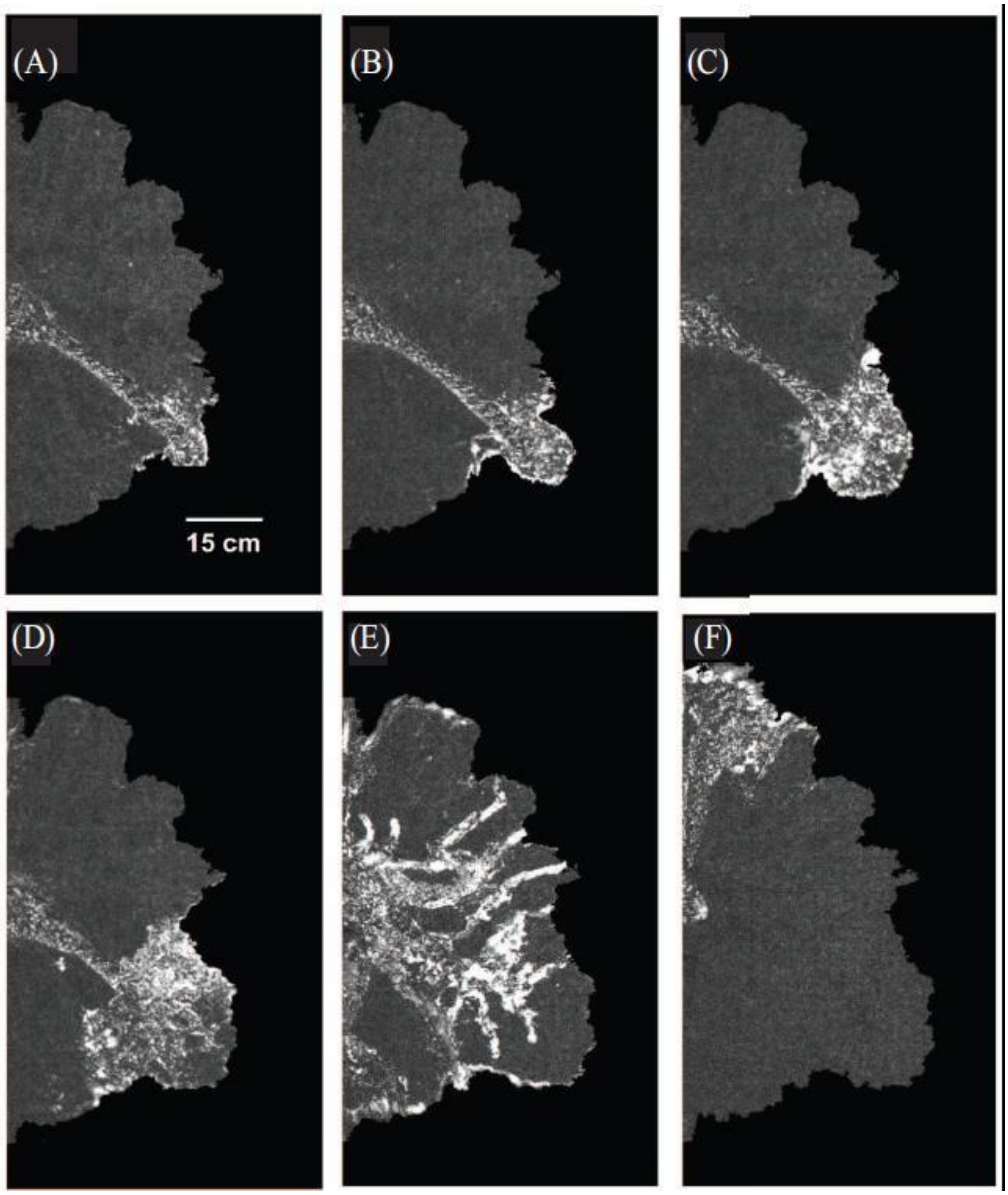

Figure 6

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Highlights

- A review paper examining the role of experimental modelling in alluvial fan research
- Long history of using experimental alluvial fans to verify fundamental theory
- Experimental fans have improved understanding of flow processes, avulsions mechanics and autogenic forcing
- Potential to use experiments for improved understanding of stratigraphic preservation and extra-terrestrial fans

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