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Debris-flow dominance of alluvial fans masked by runoff reworking and weathering

Tjalling de Haas [a,*], Dario Ventra [a], Patrice E. Carbonneau [b], Maarten G. Kleinhans [a]

[a] Faculty of Geosciences, Utrecht University, PO-Box 80115, 3508 TC Utrecht, The Netherlands
[b] Department of Geography, Durham University, DH1 3LE Durham, UK

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ABSTRACT

Arid alluvial fan aggradation is highly episodic and fans often comprise active and inactive sectors. Hence the morphology and texture of fan surfaces are partly determined by secondary processes of weathering and erosion in addition to primary processes of aggradation. This introduces considerable uncertainty in the identification of formative processes of terrestrial and Martian fans from aerial and satellite imagery. The objectives of this study are (i) to develop a model to describe the sedimentological and morphological evolution of inactive fan surfaces in arid settings, and (ii) to assess the relative importance of primary processes of aggradation and secondary processes of weathering and reworking for surface morphology and sedimentology and for the stratigraphic record. We studied an alluvial fan characterized by a recently active sector and a long-abandoned, inactive sector along the coast of the hyperarid Atacama Desert. Here, rates of primary geomorphic activity are exceptionally low because of extreme aridity, while weathering rates are relatively high because of the effects of coastal fogs. Long-term processes of fan aggradation and reworking were determined through sedimentological facies analysis of stratigraphic sections. Ground surveys for textural and morphological patterns at the fan surface were integrated with remote-sensing by an Unmanned Airborne Vehicle (UAV). Discharges and sediment-transport capacities were calculated to estimate the efficiency of secondary runoff in reshaping the inactive fan sector. Stratigraphic sections reveal that the fan was dominantly aggraded by debris flows, whereas surface morphology is dominated by debris-flow signatures in the active sector and by weathering and runoff on the inactive sector. On the latter, rapid particle breakdown prevents the formation of a coarse desert pavement. Furthermore, relatively frequent local runoff events erode proximal debris-flow channels on the inactive sector to form local lag deposits and accumulate fine sediment in low-gradient distal channels, forming a well-developed drainage pattern that would suggest a runoff origin from aerial images. Nevertheless, reworking is very superficial and barely preserved in the stratigraphic record. This implies that fans on Earth and Mars that formed dominantly by sporadic mass flows may be masked by a surface morphology related to other processes.

1. Introduction

Alluvial fans are prominent depositional landforms at the transition between highlands, which provide debris sources, and adjacent basins that offer long-term sediment accommodation (Harvey, 2010). One fundamental goal of alluvial fan research has been to link fan surface features with formative processes (e.g., Hooke, 1987; Whipple and Dunne, 1992; Blair and McPherson, 1998; Gómez-Villar and García-Ruiz, 2000; Blair, 2002; Volker et al., 2007). However, whereas many kinds of subaerial processes and their related landforms are observable over different time scales, alluvial fans pose particular challenges to direct interpretation. While aggradation of these landforms occurs from highly episodic runoff and mass-flow events and often concentrates on an active lobe comprising a small area of a fan surface, most of the time fans are subject to secondary processes of weathering and erosion by fluvial and/or aeolian activity, which may have a significant effect on the final morphology of these landforms (Blair and McPherson, 1994, 2009). For example, in arid environments weathering and erosion progressively reduce clast size and relief on long-abandoned fans resulting in the development of desert pavements and subdued, incised surfaces (e.g., Wells et al., 1987; McFadden et al., 1989; Ritter et al., 1993; Al-Farraj and Harvey, 2000; Matmon et al., 2006; Frankel and Dolan, 2007).

A fan surface is dominated either by primary processes of deposition or by secondary processes that modify the original depositional morphology. Which of these processes dominate depends on the balance between the characteristic time scales to cover and build morphology by primary deposition and to modify morphology by secondary processes, here expressed as a morphological factor M:

$$M = \frac{T_{deposition}}{T_{modification}} \quad (1)$$

* Corresponding author. Tel.: +31 30 2532778.
E-mail address: t.dehaas@uu.nl (T. de Haas).

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wherein $T_{deposition}$ is the time needed for an initial surface to become entirely covered by a primary deposit, and $T_{modification}$ is the time scale required for secondary processes of weathering and erosion to remove or modify the typical morphology of primary deposits. The morphology of fans with $M > 1$ is dominated by primary processes of deposition, whereas surfaces with $M < 1$ are dominated by secondary processes, which do not cause significant aggradation. For example, Blair and McPherson (1994) suggested that the origin of many alluvial fans may have been misinterpreted because of secondary reworking of original surface morphology. This mainly applies to alluvial fans with low recurrence intervals of depositional events and high rates of reworking, but without significant net aggradation by secondary processes. Because of the potentially misleading surface morphology and texture, the origin of such alluvial fans should ideally be inferred from stratigraphic sections that provide independent evidence for the dominant processes of long-term fan formation. The question is then to what extent the surface morphology reflects the primary process of fan formation. This needs to be unraveled for application to remote terrestrial and planetary alluvial fans that can only be interpreted from satellite imagery.

The objective of this study is to determine the relative importance of debris flows and fluvial reworking on alluvial fan surface morphology and texture and stratigraphic record. Specifically we aim to (i) construct a conceptual model of arid fan surface evolution after abandonment; (ii) compare our specific example to those of other terrestrial arid environments; and (iii) assess the implications of fan surface modification by weathering and fluvial reworking for the aerial recognition of fan formative processes on Earth and on Mars.

We analyze this on a fan along the Pacific coast of the hyperarid Atacama Desert in northern Chile (Fig. 1), where average rates of primary geomorphic activity are exceptionally low (e.g., Dunai et al., 2005; Nishiizumi et al., 2005). The fan shows a distinctly bipartite morphology, with a proximally incised active sector flanked by long-abandoned, inactive sectors enabling the comparison of the effect of primary versus secondary processes through an active fan surface where $M > 1$ and an inactive fan surface where $M < 1$.

Complementary sources of information were combined. First, we used sedimentological analyses of incised sections and surface deposits to independently identify dominant processes of long-term fan aggradation as well as the genetic characterization of different morphosedimentary facies at the surface. This provided the evidence to distinguish between primary processes of fan aggradation and secondary processes of surface reworking. Second, remotely sensed hyperspatial imagery with <10 cm resolution (see Carbonneau et al., 2012) was obtained to study spatial patterns of morphology, texture, and sorting calibrated by surface sediment sampling. We created maps of median particle size (D_{50}) and digital elevation (DEM), which we used to quantify textural and morphological differences between the active and inactive fan sectors with emphasis on two different secondary processes: weathering and fluvial reworking. Third, we calculated flow and sediment-transport capacity to evaluate the potential of runoff in reshaping the inactive fan sector. Finally, we combined the results obtained from these complementary approaches to propose a conceptual model for surface evolution after abandonment. The paper is organized as follows. First we describe the general geological and climatic setting of the study location followed by the detailed methods. We then compare the active and inactive sectors of the fan in sedimentological analysis followed by the surface morphology and texture analyses, after which we propose a model for fan surface evolution by primary and secondary processes. The discussion focuses on comparison to other arid environments and implications for inference of primary process from imagery on Earth and on Mars.

2. Geological and climatic setting

The Coastal Cordillera of northern Chile is a prominent topographic feature extending more than 700 km along the active tectonic margin between the oceanic Nazca Plate and the continental South American Plate (Armijo and Thiele, 1990; Hartley et al., 2005). Owing to crustal thickening and uplift, the Cordillera has an average altitude of 1000 m and locally reaches elevations in excess of 2000 m above sea level, forming a steep escarpment that terminates with precipitous slopes onto the Pacific coast. The dominant lithologies of the Cordillera are Jurassic andesites and associated granitic intrusions (Ferraris and Di Biase, 1978; Hartley et al., 2005), which feed steep colluvial systems and numerous alluvial fans at the base of the coastal escarpment, as well as discontinuous shoreline deposits.

The hyperarid Atacama Desert region has extremely low precipitation rates that average <5 mm/y between 18° and 24°S (Houston and Hartley, 2003), and no precipitation is commonly recorded over many consecutive years. The major source of humidity along the Atacama Desert coast is the camanchaca, a recurrent coastal fog condensed from subsiding warm air along the eastern margin of the SE Pacific Anticyclone that interacts with the cold Humboldt Current near sea level (Araveni et al., 1989; Marchant et al., 2007). In general, the coastal fogs are prevented from reaching far into the continental interior as they are commonly entrapped along the oceanward margin of the Coastal Cordillera (Hartley et al., 2005). Because of the near absence of precipitation, alluvial depositional events are very rare in the Atacama Desert. Near Antofagasta, depositional events are estimated to have occurred approximately once every 210 years between 5 and 1 Ka, and once every 40 years over the last thousand years (Vargas et al., 2006). However, seven debris-flow events are recorded in Antofagasta between the years 1916 and 1999 (Vargas et al., 2000), and several studies linked geomorphically effective floods to severe El Niño events in the Atacama region (e.g., Vuille, 1999; Vargas et al., 2000, 2006; Houston, 2006).

Salt-weathering is the dominant weathering mechanism in the Atacama Desert (Berger, 1993; Berger and Cooke, 1997; Goudie et al., 2002). Along the Coastal Cordillera, salts are deposited mostly by condensation of the camanchaca and, to a lesser extent, are blown landward by winds from the ocean. The camanchaca contains considerable amounts of dissolved salts, mainly nitrates (Eriksen, 1981) and sulfates (Schemenauer and Cereceda, 1992). Large quantities of salts combined with the prolonged inactivity of geomorphic surfaces form an ideal precondition for pervasive salt-weathering, particularly effective on loose debris at the surface of coastal fans (Berger, 1993; Berger and Cooke, 1997; Hartley et al., 2005).

Fans along the Atacama Desert coast are predominantly formed by debris flows, but colluvial cones and fluvial surfaces do occur (see Hartley et al., 2005; de Villiers, 2013, for descriptions of fans in the larger area). We selected a fan (Fig. 1) with an area of 1.05 km^2 and a maximum width of 950 m. Fan slope is ~11° at the apex and generally declines to ~6° near the fan toe. The average slope is 8.3°, the apex is located at 247 m above sea level, and the fan toe terminates into the Pacific. The fan is fed by a steep catchment with an area of 3.42 km^2 and a maximum height of 1204 m above sea level conveying runoff from the Coastal Cordillera toward the Pacific. Bedrock in the catchment mainly consists of Jurassic andesites of the La Negra Formation (Ferraris and Di Biase, 1978). Pedogenic cover and vegetation are completely absent owing to the extreme local aridity.

The fan surface can be divided into two distinct morphosedimentary domains because of a large incision at the apex (Figs. 1, 2): (i) a relatively young sector formed by relatively recent depositional events ($M > 1$), flanked by (ii) two older sectors that have undergone a long period of depositional inactivity, while being exposed to secondary processes of weathering and erosion for a prolonged period ($M < 1$). The younger sector has a maximum distal width of 250 m and comprises ~25% of the total fan surface.

3. Methods

We assessed primary aggradational processes on the fan by sedimentological analyses of incised sections and characterized patterns of surface morphology and texture by combining a ground survey with hyperspatial