Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars

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[1] Longitudinal profiles from six alluvial fans surveyed in southwestern California have quantitative attributes that can distinguish formation processes. The radial slope of fans where debris flow processes dominated is constant while fluvially-fed fans have a concave-upward shape. We find the power law regression of upstream slope-distance profiles is the preferred approach for assessing concavity. Concavity index, the exponential determined via power law regression analysis, is an accurate reflection of the magnitude of the concavity and thus a qualitative measure of the relative influence of fluvial processes on the fan. Fan length and surface gradient are inversely correlated: debris flow fans are shorter and steeper (>15°) than their fluvial counterparts. The results of this investigation provide criteria to evaluate hypothesized formation processes and provide constraints on the amount of fluid and timescales involved in the generation of comparably-sized fans within Mojave Crater, Mars. **Citation:** Williams, R. M. E., J. R. Zimbelman, and A. K. Johnston (2006), Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars, *Geophys. Res. Lett.*, *33*, L10201, doi:10.1029/2005GL025618.

1. Introduction

[2] In the Xanthe Terra region of Mars, unique fan-shaped landforms are observed associated with the walls of 60-km diameter Mojave Crater (name provisionally accepted by the IAU; 7.6°N, 33.0°W) in high-resolution Mars Orbiter Camera (MOC) images (Figure 1). These ~500-m radial length fans share many morphologic attributes in common with terrestrial alluvial fans including a semi-conical form, branching tributary network, distributary channels and incised channels [*Williams et al.*, 2004a, 2004b] (R. M. E. Williams et al., Fans in 'Mojave' Crater, Mars: Evidence for impact-induced atmospheric precipitation, submitted to *Icarus*, 2006) Collectively, these landforms have attributes consistent with surface overland flow of fluids and formation of fans by water and gravity-driven alluvial sedimentation. However, many aspects of their formation remain uncertain or ill-constrained including the amount and source (atmospheric precipitation or groundwater) of fluid involved as well as the duration of fan formation.

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[3] An alluvial fan is a semi-conical form that occurs when water-transported material emerges, at a point termed the apex, from an upland onto a lowland. Alluvial fans are present in a multitude of diverse settings and aggradation occurs in response to a variety of factors. Terrestrial alluvial fan research has focused on elucidating the roles of climatic, hydrologic, tectonic and lithologic factors controlling fan development [e.g., *Harvey*, 1997]. Two categories of primary processes are responsible for terrestrial alluvial fan aggradation: 1) sediment-gravity processes wherein large volumes of sedimentary material, including interstitial fluid, if any, are transported downslope under the influence of gravity as a direct result of the reduction of ground stability or resisting forces, and 2) fluid-gravity (water-flow) processes that result from precipitation or snowmelt-fed surface runoff that transports sediment downslope [*Blair and McPherson*, 1994]. Differentiating between these two end members provides constraints on the amount of fluid and timescale of fan formation. Debris flows, a sediment-gravity process, emplace large volumes of sediment with relatively little fluid component [47%–77% sediment concentration by volume; *Costa*, 1998] in short periods of time. In contrast, alluvial fans constructed primarily of fluvial processes (sediment concentration in water flows <20% by volume; hyperconcentrated flows 20%–40%) [*Costa*, 1998] build fans incrementally by small amounts typically associated with low occurrence, high magnitude storms. *Moore and Howard* [2005] compared large scale (>10 km length) Martian fans to terrestrial alluvial fans and documented the general trends in alluvial fan morphology are similar on the two planets.

[4] The purpose of this investigation is to quantitatively characterize small (<1 km radial length) terrestrial alluvial fans to identify the attributes of the fan shape diagnostic of alluvial sedimentation processes. We compared the observed bisectional fan profile characteristics to fan formation mechanisms (debris versus fluvial flows) that were independently identified in prior studies. Here we report on results based on measurements made of fans in southwestern California that reveal potentially useful discriminating attributes of fan shape related to aggradation process. This investigation provides additional criteria to evaluate hypothesized formation processes of the Mojave Crater fans, one step toward constraining the amount of fluid and timescales involved in their generation.

2. Methodology

2.1. Field Sites

[5] We selected six alluvial fans in southwestern California that represent a continuum of formation processes:

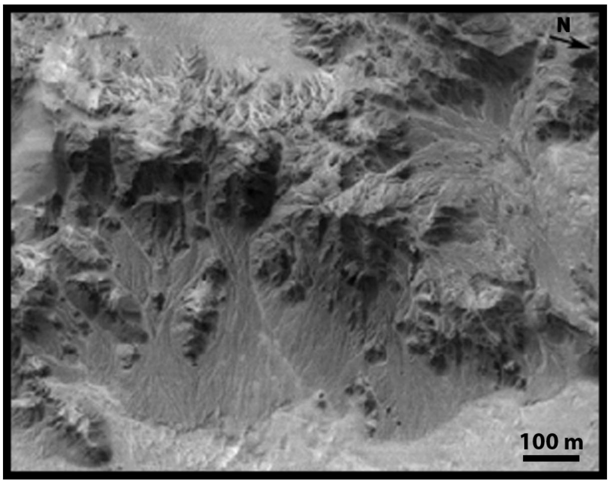

Figure 1. Portion of MOC image R07-01504 illustrating coalescing fans forming a broad apron of material within Mojave Crater. Illumination from lower left.

fluvial, debris flows (debris cones), and fans formed by a combination of mechanisms (composite fans). Five of the fans are located on the eastern side of Soda Mountains (35.2°N, 116.1°W), south of Baker, CA, while a sixth fan is on the eastern flank of Eagle Mountain (36.2°N, 116.4°W) south of Death Valley Junction, CA (Figure 2). Fans associated with Eagle Mountain, comprised of volcanic and sedimentary rock, are classified as fluvially-dominated by *Denny* [1965]. *Harvey and Wells* [2003] conducted alluvial fan stratigraphy, sedimentologic and geomorphic mapping of the Soda Mountain fans, which have good age-control due to regional correlation with dated late Pleistocene Lake Mojave shorelines. It is the number and duration of flow events determined by *Harvey and Wells* [2003] that is used to qualitatively rank the alluvial fans in terms of process shown in Table 1 (range from fluvial to debris flow dominated). The catchment of the Soda Mountains is principally metavolcanic rocks. The sequence of formation for Johnny Fan is dominated by fluvial processes following early stage major hillslope debris flows. In contrast, the Mesquite and Steve Fans transitioned from fluid, muddy debris flows to coarser boulder-size clast debris flows over the formation period. While both fans experienced periods of fluvial modification, the duration of fluvial activity was longer for the Mesquite Fan. Finally, two debris cones (DC) were also surveyed at Soda Mountain.

Figure 2. Schematic map illustrating location of field sites.

[6] By selecting comparably-aged alluvial fans in the same region, we minimize the number of factors that influenced their development. These fans share a common climatic/geologic setting. Fan formation processes occurred during the Late Quaternary in response to climatic change rather than base-level change [*Harvey and Wells*, 2003]. Although many attributes of the Mojave Crater fans are unknown (lithology, grain size, etc.), it is presumed to be a tectonically stable setting and it is likely that climatic conditions were a key factor in their development. In these aspects, the Mojave Crater fans are similar to those examined in this study.

2.2. Longitudinal Profiles

[7] To document the fan shape, we acquired radial longitudinal profiles midsection on the fan from a point beyond the fan toe (termination point of the alluvial fan) to the fan apex. High precision topographic measurements of terrestrial alluvial fans were made using the Trimble 4800 Total Station, a carrier-phase Differential Global Positioning System (DGPS). Differential correction of GPS data allows positions to be determined relative to the base station with a horizontal accuracy of ~1 to 2 cm, and vertical accuracy of ~2 to 4 cm.

2.3. Regression Analysis of Fan Profile Shape

[8] No standard method currently exists for plotting alluvial fan data (e.g., downslope vs. upslope) and a variety of equations have been applied to quantify fan shape. Considerable differences in the resulting analysis are apparent based on methodology [*Shepherd*, 1984]. We evaluated multiple regression analysis approaches to ascertain which method(s) best discriminate formation mechanism. Prior studies have focused on analyzing the longitudinal profile (e.g., *Moore and Howard* [2005] quantified concavity by fitting a negative exponential to the downslope fan longitudinal profile). However, we found, plotting slope as a function of distance is a useful way to represent fan shape (Figure 3B). Unlike elevation, slope is independent of location along the profile and provides numerically unrelated data points for analysis. We constructed slope-distance plots and two regression analyses techniques were applied to assess concavity: an exponential regression (equation 1), where S is gradient, C is a constant, b is concavity and x is

Table 1. Regression Analysis of Longitudinal Profiles for Southwest California Fans

Fan	Type[a]	Length, m	Average Slope	Linear R^2	Exp. R^2	Power R^2
Eagle	Fl-D	810	5.0	0.948	0.954	0.786
Johnny	Fl-M	376	6.2	0.991	0.993	0.866
Mesquite	Fl-M	455	13	0.979	0.988	0.149
Steve	DC	299	14	0.992	0.996	0.847
DC 20	DC	91	16	0.995	0.997	0.836
DC 24	DC	99	17	0.997	0.997	0.320

[a]Type of alluvial fan classified by *Denny* [1965] for Eagle Mountain and by *Harvey and Wells* [2003] for all other sites; Fl-D = fluvially dominated, Fl-M = fluvially modified, DC = debris cone.

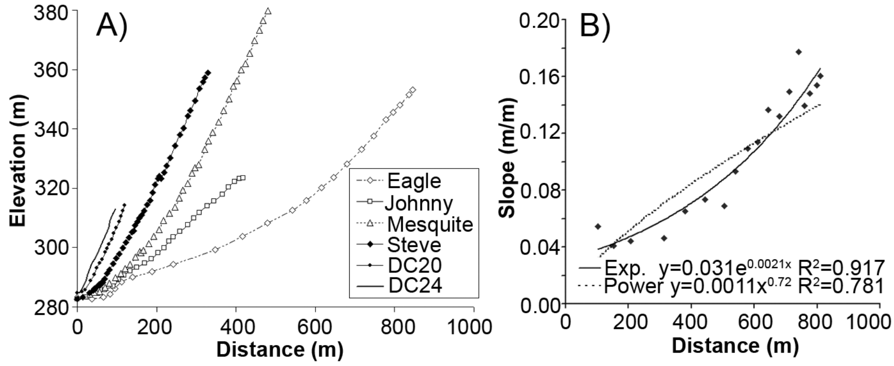

Figure 3. (a) Longitudinal profiles of alluvial fans in southwest California. Fans are listed in the legend from the fluvially-dominated endmember (Eagle) to the debris flow-dominated debris cones (DC 20 and DC 24). Vertical exaggeration is ~8X. (b) Slope-distance plot for Eagle fan.

distance upslope, here measured from an arbitrary point beyond the fan toe [e.g., *Howard and Craddock*, 2000], and a power law regression (equation 2), where S is gradient, K is steepness index, L is distance upslope (here measured from an arbitrary point beyond the fan toe) and θ is concavity index, a measure of the degree of concavity with higher values reflecting stronger concavity [e.g., *Brush*, 1961].

$$S = C\ e^{bx} \tag{1}$$

$$S = K\ L^{\theta} \tag{2}$$

Through regression analysis, the best fit parameters to the observed data for each function type yield values for concavity (b) and concavity index (θ).

3. Results and Implications

[9] The radial longitudinal profiles acquired via DGPS are illustrated in Figure 3a. Table 1 summarizes the results of multiple regression methods applied to the longitudinal profiles while Table 2 lists the best fit parameters derived from curve fits applied to the slope-distance plots. Note that the fans are listed by formation type in both tables ranging from the fluvial end-member (Eagle Mountain) to debris cones (DC20 and DC24). Several potentially useful attributes of fan morphology were observed, many of which are detectable in remotely sensed data for Mojave Crater fans. A complete description of the bisectional fan shape is dependent on analysis of both the longitudinal profile in conjunction with the slope-distance plot.

[10] 1) We performed regression analysis on the longitudinal profiles to examine various plotting standards. Due to the positive association between variables, we advocate an upslope plotting method. Considerable variability in the derived best fit coefficients arises depending on the selection of the origin. We define the origin as the slope break between the toe and fan surface.

[11] 2) Fan length and the surface gradient are inversely correlated. In these examples, shorter fans (<200 m) resulted from debris flows and have a steeper average fan slope (>15°) relative to longer (>400 m), shallower (<7°) fans formed via fluvial flow. These results are consistent with prior work on terrestrial alluvial fans that show fan slope increases as grain size increases, as summarized by *Blair and McPherson* [1994]: clast-rich debris flows or bouldery sheetflood deposits generate slopes between 5°–15° while sandy, pebbly and cobbly sheetflooding results in shallower slopes, 2°–6°. Thus, the two main factors controlling the average slope and variations in slope along the radial profile are (a) primary fan formation process and (b) sediment size available for fan construction [*Harvey*, 1997]. *Moore and Howard* [2005] contend that the effect of lower Martian gravity will result in a greater magnitude difference in fan surface gradient between the two formation processes; thus, Martian debris flow deposits would be steeper and fans dominated by water flows would be shallower relative to their terrestrial counterparts.

[12] 3) All six longitudinal profiles had high degrees of correlation with the linear and exponential functions (Table 1). A high correlation coefficient for linear regression of the fan surface ($R^2 > 0.99$) appears to be an accurate predictor of debris flow dominated fans (Steve Fan, Debris cones 20 and 24). The power function is inadequate for most longitudinal profiles, a result consistent with regression analysis of river longitudinal profiles [e.g., *Shepherd*, 1984].

[13] 4) A power law regression of slope against distance provides the most useful method of describing and comparing curvature. The correlation coefficient, R^2, reflects both profile curvature and ruggedness; profiles with the smoothest curvature and the least variable slope changes have higher R^2 values.

[14] 5) Fluvially-fed fans had a concave-upward profile. The correlation coefficient associated with power law and exponential regressions applied can differentiate strong concavity from subtle concave form. These preliminary results indicate the concavity index, θ, is an accurate

Table 2. Regression Analysis of Slope-Distance Plots for Southwest California Fans

Fan	Concavity	Exponential R^2	Concavity Index	Power R^2
Eagle	0.0021	0.917	0.72	0.781
Johnny	0.0040	0.666	0.42	0.666
Mesquite	0.0026	0.481	0.40	0.468
Steve	0.0028	0.323	0.38	0.402
DC 20	0.0052	0.322	0.28	0.296
DC 24	0.0012	0.019	0.07	0.033

reflection of the magnitude of the concavity and that the power law regression is the preferred approach for assessing concavity. The magnitude of the concavity index shows a consistent trend with fan formation process and can be used as a qualitative measure of the degree of fluvial processes that operated on the fan.

[15] 6) In the case of fans with a complex history, careful examination of the regression analysis is necessary to detect the formation processes involved. For example, Johnny Fan preserves the signatures from both fan formation processes: a relatively shallow average slope and modest concavity. The strong correlation to the linear fit reflects the history of major hillslope debris flows in the Late Pleistocene. The Johnny Fan experienced fluvial activity over much of its history, which is evident in the relatively high concavity index value (0.42) together with a high correlation coefficient (0.666). Interestingly, despite ~10,000 years of dominantly fluvial activity on the Johnny Fan, only a modest concavity has developed.

[16] The findings summarized above from terrestrial analogs will be instrumental in determining the formation processes that resulted in the fans within Mojave Crater. Concavity index, together with additional morphological relationships (for example, correlation of gradient and drainage area and between gradient and basin relief as discussed by *Moore and Howard* [2005]) all serve to provide a more complete picture of the processes and duration of activity involved in fan formation. Topographic data can be derived from Mars Orbiter Laser Altimeter (MOLA) where along track MOLA shots cover roughly 170 meters on the Martian surface, typically separated by 300 meters from neighboring shots [*Zuber et al.*, 1992; *Smith et al.*, 2001]. This resolution poses a challenge for evaluating sub-kilometer scale fans. Individual shot points from multiple MOLA ground tracks may increase the resolution. In addition, stereo imaging systems have demonstrated that decameter-scale topography can be produced in targeted areas of Mars. Future work will also use existing MOC stereo pairs of Mojave Crater fans and forthcoming images from the High Resolution Stereo Camera (HRSC) aboard the European Mars Express spacecraft to quantitatively characterize fan morphology.

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