Alluvial Fans of Northern Chile as an Analog to Mars

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Introduction and Context

Numerous alluvial fans have been identified on Mars, including one in Gale Crater, landing site of MSL Curiosity. These fans mostly date to the post-Noachian [1], a period generally characterized by a cold and hyperarid climate [2]. Martian alluvial fans are a unique target of exploration as they are one of Mars' few depositional (rather than erosional) fluvial landforms and they may be representative of the last major episode of widespread fluvial modification of the planet's surface. Deciphering the climatic environment capable of forming such fluvial features is challenging but significant in furthering our understanding of the potential late-stage habitability of Mars.

These alluvial fans are typically found within 50-100km diameter, flat-floored craters and tend to be characterized by their large size (tens of kilometers in length), gentle gradient (~2°), highly eroded surfaces, and sourcing from deeply incised drainage basins along the interior crater rims. [3,4] Some of the best exposed fans for study lie within Saheki Crater **(Figure 1).** Our analysis of these fans [5] indicates that they were primarily formed by a distributary channel network through many hundreds of flow events which were fed by the melting of snow in the upland basins, a conclusion echoed in studies of other fans [3,6]. However, extensive aeolian erosion has erased many of the definitive signatures of flow processes, making it difficult to decipher the formative conditions during fan formation.

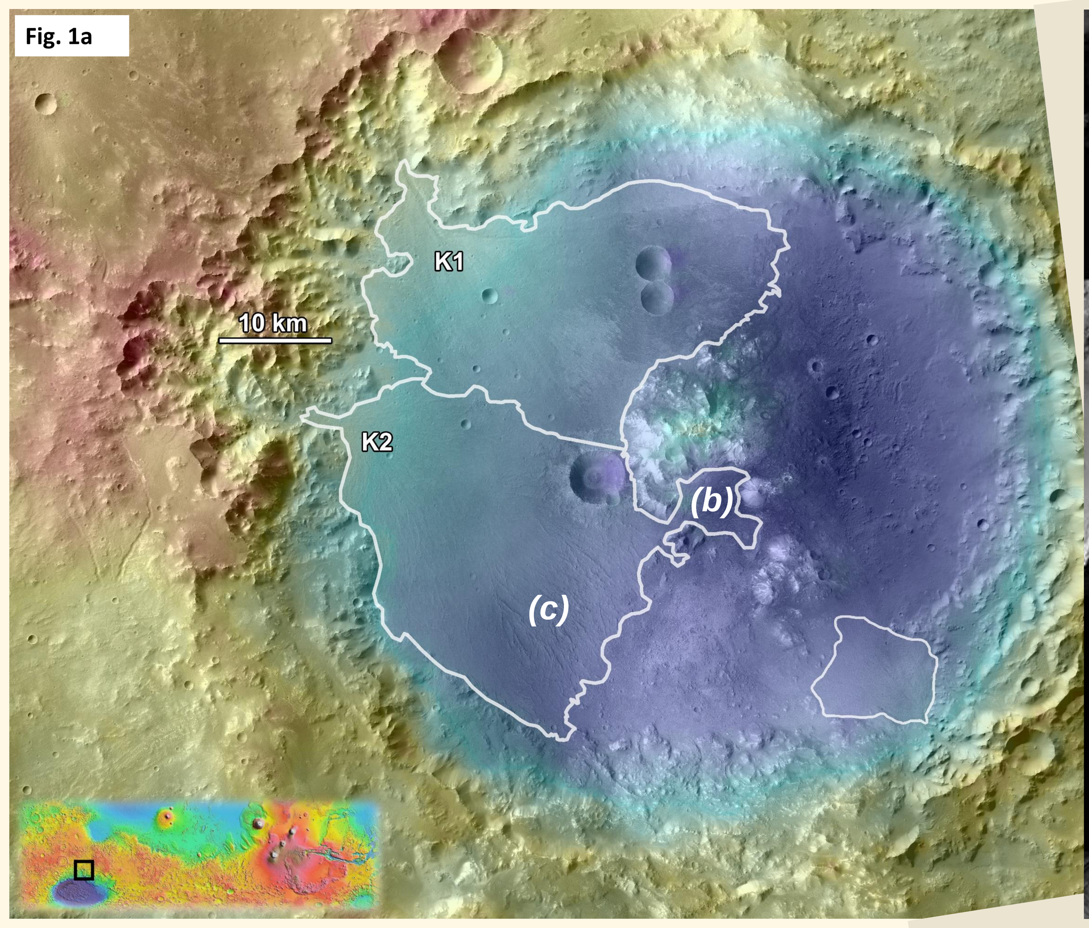
Martian fans contrast with the typical small size, coarse grains, and steep slopes of terrestrial fans in arid, mountainous settings [7]. However, a suite of fans in northern Chile's Atacama Desert **(Figure 2)** appear to constitute a unique terrestrial analog to the fans. The Atacama fans are similar in size and morphology to those found on Mars, receive very little rainfall, and terminate in flat-lying basins. We undertook a field study of this fan system in order to refine the potential processes responsible for forming the martian fans.

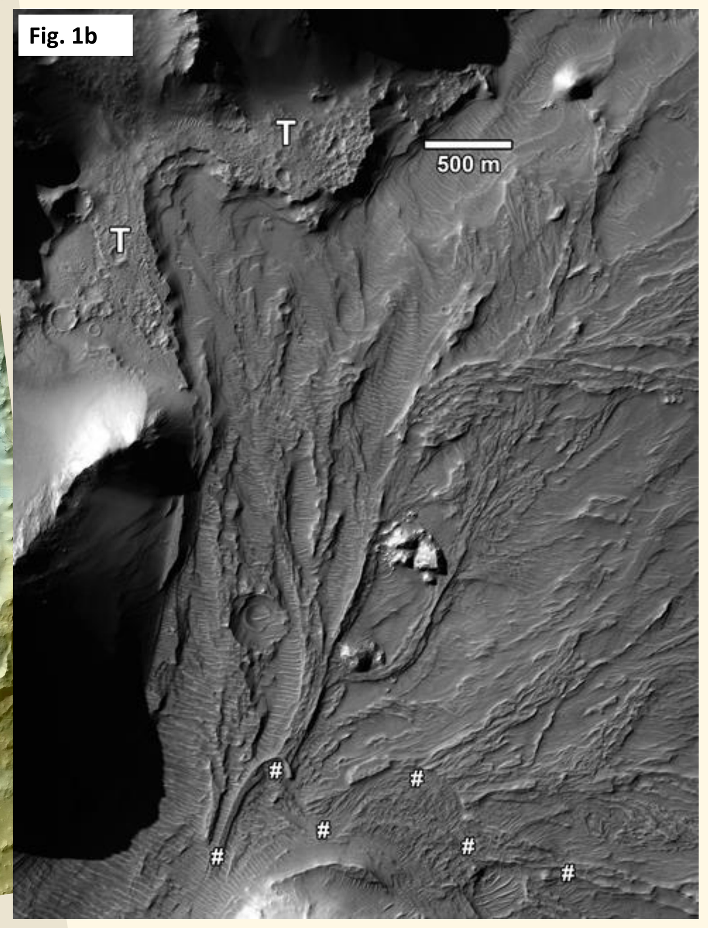
Methods and Results

Our study involved a combination of remote sensing, field work, and laboratory analysis. Despite the hyperarid conditions, flow events do occur with appreciable frequency as evidenced by the disruption of vehicle tracks, footprints on recent deposits, and sediment deposition on roads and railroad tracks. Distributary channel widths are typically 3-10m wide and 1m deep, with overbank deposit mudflows extending laterally outward up to 150m from the channel. Mudflows have a maximum thickness of ~25cm and thin out with distance from the main channel. Channels exhibits modest sinuosity, although deposition appears to be dominated by vertical aggradation. Avulsions occur as the channel and levees aggrade through multiple flow events. Abandoned, inactive portions of the fan are predominately modified by aeolian deflation, which results in inverted topography as channels containing gravel resist erosion while sand-grained and smaller overbank material is easily removed. Paleochannels are inverted at heights of 1-2 meters above the surrounding terrain.

Quantitative analysis of flow hydrology was performed in the field. Flow velocities were estimated by measuring the superelevation of deposits on channel bends, as well as the onlap of overbank deposits onto emplaced boulders. Flows within the upper-fan channel **(Figure 3a)** are estimated to be ~4m/s while overbank deposits at the mid-fan are ~1m/s **(Figure 3b)**.

We collected 57 sediment samples which were analyzed for grain size distributions. Particle size analysis (PSA) was conducted with Beckman Coulter laser diffraction for small (<2mm) sediments and four differently sized sieves for larger sediments. Mudflow deposits typically contain 10-25% clay, 10-50% silt, 15-60% sand, and a few percent granules and fine pebbles, although there is significant variation between deposits.





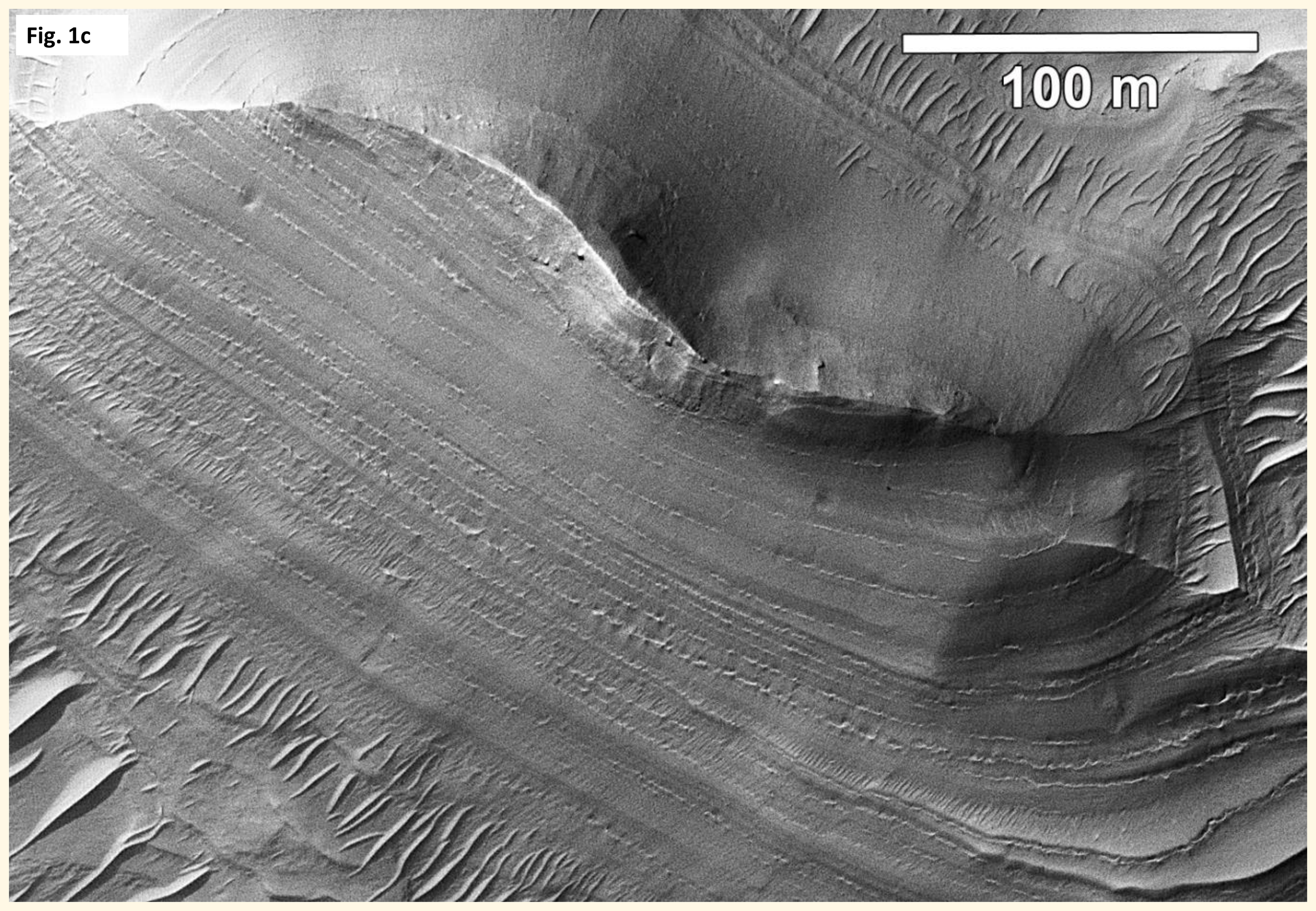
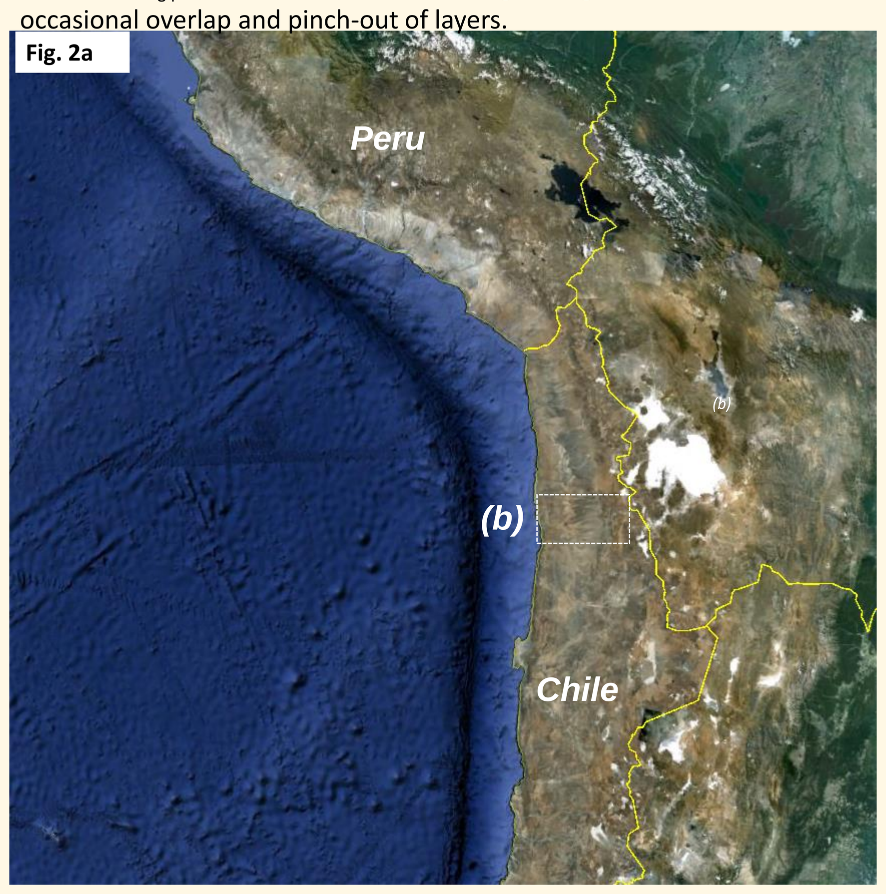
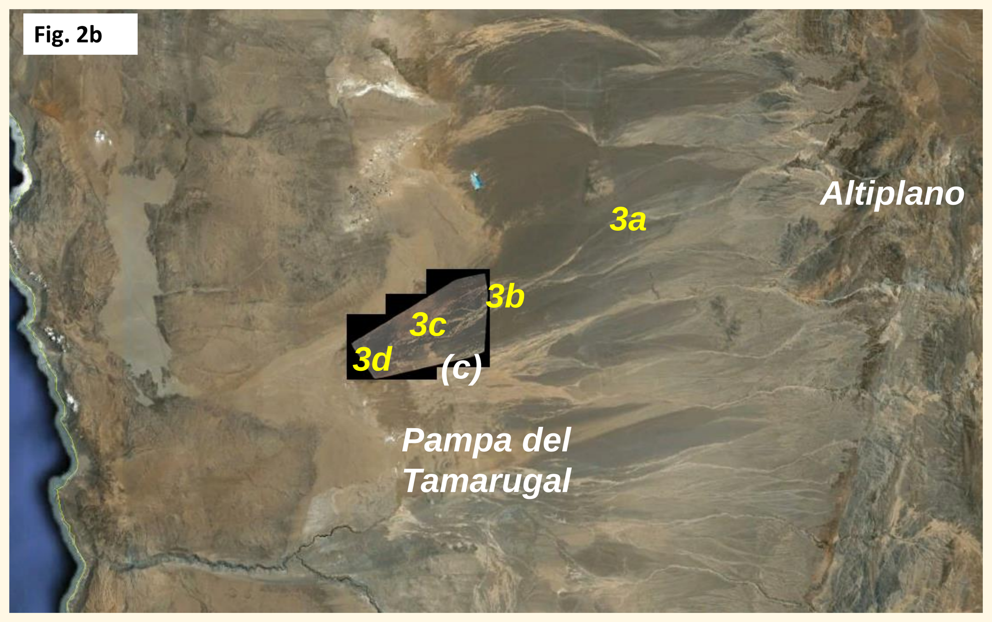
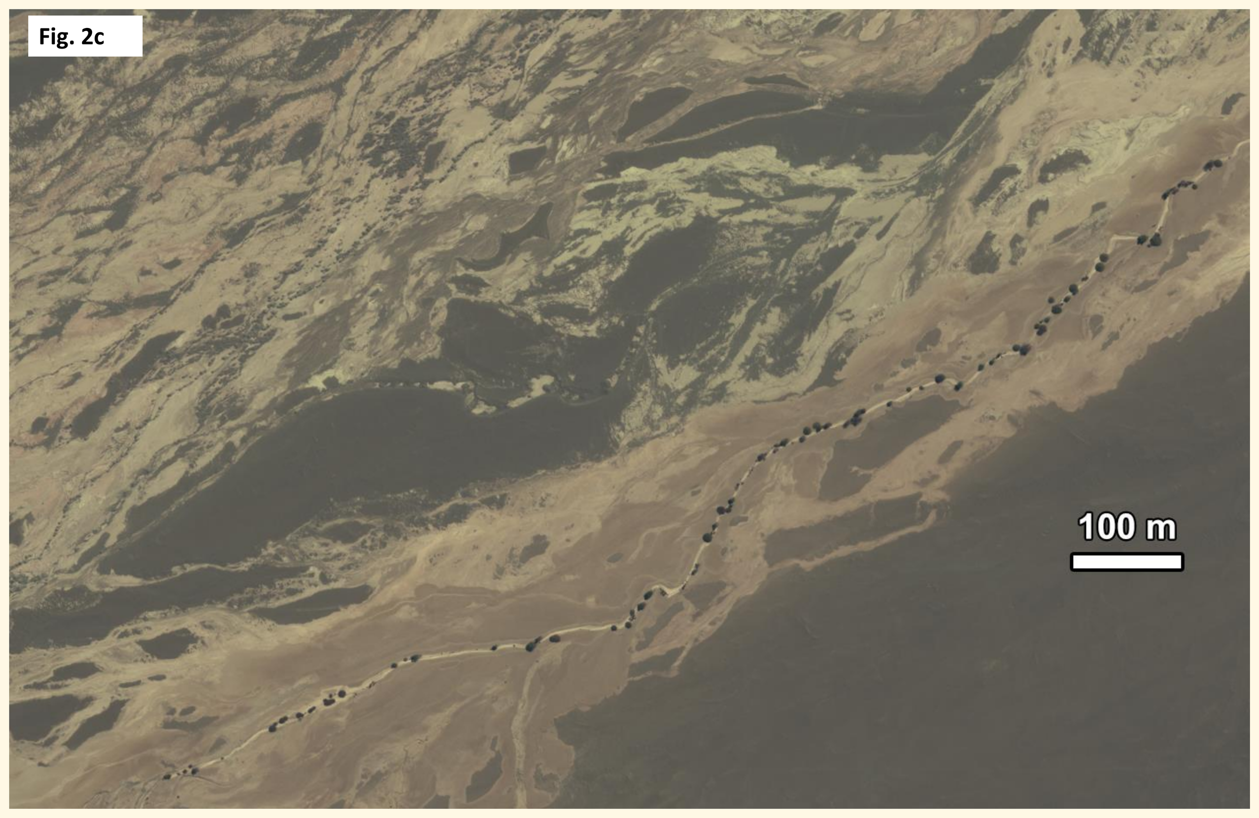


Figure 1. (above) Saheki Crater, Mars. North is up. (21.7° S, 73.2° E, 85km diameter) **(a)** CTX mosaic overlying MOLA-derived topography. Inset at bottom left indicates location. Alluvial fans are outlined in white. Fans are ~35km long with a 1.8° gradient and source basin relief of 1.75km. **(b)** Part of HiRISE image ESP_27177_1580 showing inverted distributary ridge network on a splay of the Saheki K2 fan. "T" indicates flat-lying deposits, possibly remnants of terraces or playa. We interpret the ridges to be mantled with gravely sediment deposited by low-sinuosity meandering. "#" symbols follow a sinuous distributary. Channels exhibit poor branching and occasionally show evidence for scroll bars and natural leveeing. Ridges have been removed in areas, indicating that bedload material is transportable by the wind. A vast amount of material (crudely estimated at 5-7km^3) has been removed from the fan. **(c)** HiRISE image PSP_007688_1575 close-up of ridge wall. Relief is ~70meters from crest to slope base. Boulders at >pixel size are rare and we infer a D_{84} of ~20cm. Note interbedding of ridge crest material with smooth, almost parallel sheets of finer grained material with occasional overlap and pinch-out of layers.

Figure 2. (below) Fans in Pampa del Tamarugal, Chile. North is up. Images (a) and (b) from Google Earth. **(a)** Regional context. The fans are located along a 140km transect and flow westward from the Andes Mountains onto the Playa del Tamarugal plateau. **(b)** Field location showing portion of fan complex. Quickbird image (c) is outlined in black and 3a, 3b, and 3c indicate locations of photos in Figure 3. The fan studied in is centered on 21°S, 69°W and receives only ~2mm/year rainfall on its surface, but upstream catchments (of area ~570km^2 and ~390km^2) receive precipitation of order ~0.1-1m/year. The fan is approximately ~30km long, with a gradient ranging from 1.7° at the apex to .4° near the depositional terminus and source basin relief of 2.5km. **(c)** Portion of high-resolution Quickbird image showing distributaries and overbank deposits. Individual flow deposits are easily distinguishable from one another by sharp flow margins and subtle color differences. Note near-bilateral symmetry of deposits. A few long overflow sheet deposits more than 1 km in length extend from the main distributary channel. Dark areas are inactive portions of fan mantled with granule ripples.







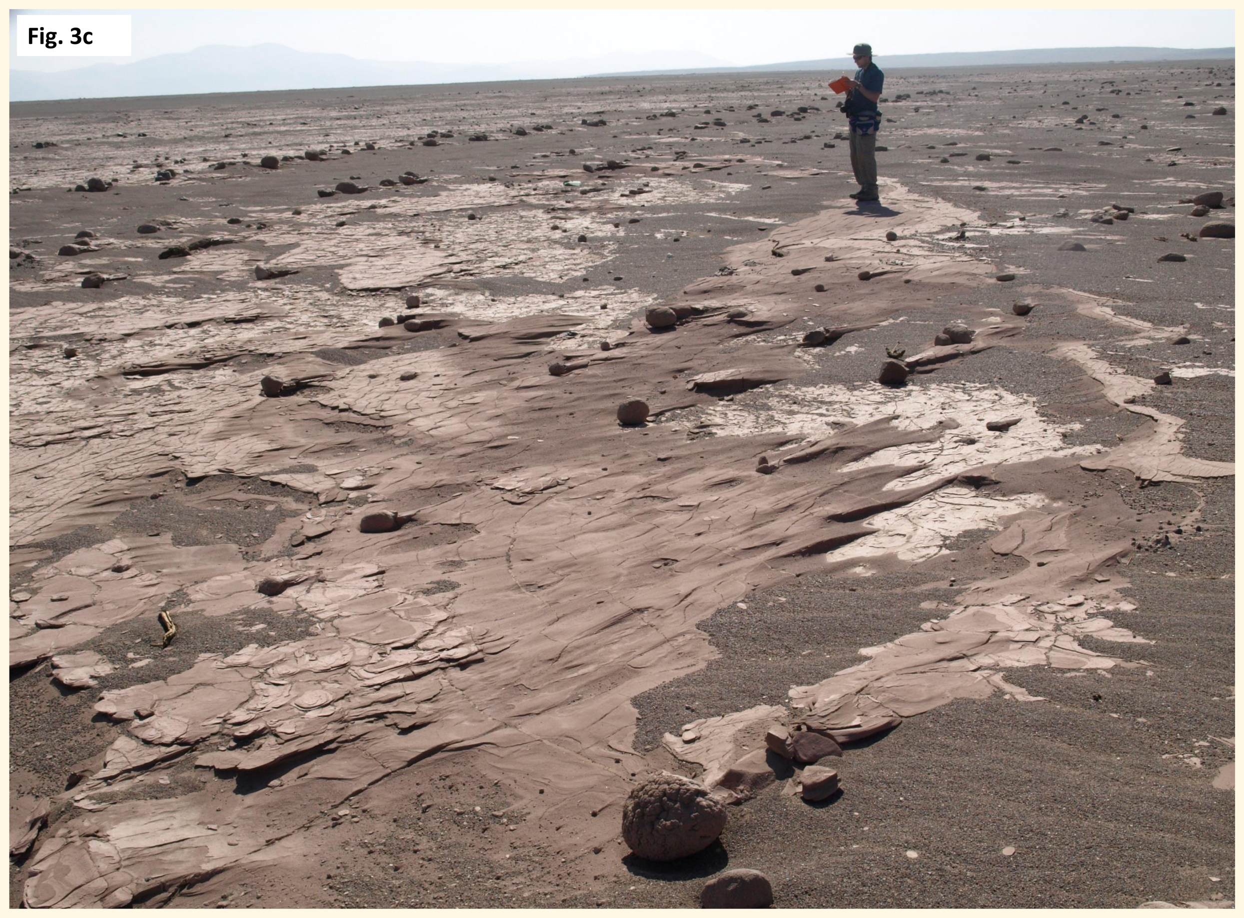


Figure 3. Photos taken along fan surface. Locations given in Figure 2b. **(a)** Upper fan exhibits incised channels and zero vegetation. Clean, cobble-sized material lies on the inner channel floor and overlays finer grained, poorly sorted, red-brown overbank material (named "Old Red"), which implies clearwater flow after the initial, more viscous debris or hyperconcentrated flow. Note how "Old Red" has plastered sidewalls of channel. Variations of thickness and slopes of frozen flows were used to constrain flow parameters. **(b)** Mid fan. Vegetation is concentrated along most recently active channel. Less pronounced contrast between viscous overbank deposits and later clearwater fluvial deposits on the channel floor. Cobbles found to be both in channel as bedload deposits and within poorly sorted massflow units, implying they are moved by a variety of mechanisms. **(c)** Lower fan. Desert pavement overlies wind-scoured fine grained overbank deposits. **(d)** Far distal fan is inactive and features sinuous inverted ridges. Very fine sand is overlain by desert pavement which becomes more rippled with distance downfan. Salt nodules are exposed at places.

Conclusions and future work

The Atacama fans constitute an exceptional terrestrial analog for the numerous fans observed on Mars due to **1. similar scale** (~30 km length, source basin relief ~2 km), and **gradient** (< 3°), **2. hyperaridity** of the environment (Atacama precipitation rate of < 2 mm/yr), **3. low channel branching density**, **4. dominance of mud sedimentation**, and **5. dominance of wind over fluvial erosion** of the inactive fan surface.

Sediment deposited on railroad tracks and roads indicates that flows have occurred within the past few decades. Vegetation is very scarce and localized to recently active flow channels. Avulsions occur frequently. The source region provides sediment of varying composition (fine grained mudstones, sandstones, volcanic ash) from the western edge of the Andes.

The exposed stratigraphy contains cobble-sized alluvium interbedded with fine-grained mudflows. Recently active flows are dominated by fine sediment with fine-grained, sheetflow-like mud deposits extending outward of the active channel for about 150m bilaterally. Well-sorted, rounded, gravel to cobble sized material on the channel floor was probably deposited by less muddy waning-stage flows. Channels on inactive portions near the fan periphery have been partially inverted in relief by wind erosion of interbedded overbank deposits.

We infer that the processes and formative environment are good analogs for those that occurred on Mars. The Atacama fans have formed through many hundreds of separate (temporally widely spaced) flows, with only a small portion of the fan receiving sediment during each. The martian fans in Saheki Crater and elsewhere likewise could not have formed in a single occurrence. Rather their formation took place over many separate events and would require periods of snow accumulation and subsequent runoff.

In addition, the Atacama fans also provide a strong analog to the topographic inversion of paleochannels. The likely similarity in grain sizes between martian and Atacama fans is suggestive of similar inversion mechanics whereby the fine-grained overbank deposits are preferentially eroded, potentially locally affected by chemical cementation.

A future field excursion to other fans in the region will provide more data with which to refine the processes responsible for forming the martian fans. In addition, quantitative landform modeling (currently in development) will further constrain variables and provide better conclusions to the climatic environment during period of fan formation.

References

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