PROCESSES INVOLVED IN THE FORMATION OF MARTIAN FAN-SHAPED DEPOSITS.
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Introduction: Martian fan-shaped deposits have varied origins. As on Earth, they can be classified as subaerial fans, true deltas, or lava deltas. True deltas (deposited where a river debouches into standing water) on Mars are either fluvial- or wave-dominated; fluvial-dominated deltas are influenced by inertia, buoyancy, and friction processes at their distributary mouths. Fan deltas, kame deltas, and grounding line wedges may also be present. To understand depositional environments and hydrologic and paleoclimatic conditions, it is important to distinguish between them. With the availability of high-resolution imagery, we can re-evaluate earlier classifications, and distinguish between several types of deltas and fan-shaped deposits.

Subaerial fans: Fan-shaped deposits may be produced by subaerial mass wasting, such as the huge Valles Marineris landslides, or as alluvial fans as at "Mojave Crater" [1].

Lava deltas: Lava deltas have a familiar deltaic form, but result from lava flowing into a body of water, as at the Banana Delta in Hawaii. A lava delta has a flat bench covered with loose rubble from explosions and subsidence [2]. Mangala Valles delta has been used in the past as proof of the existence of true fluvial deltas, based on its appearance in Viking images [3,4], but when examined at MOC NA resolution (Figure 1) it presents a surface covered by irregular pits and mounds, and no preserved distributaries. Its surface slope is 1.5° [3] but foresets cannot be observed even in the MOC image. Leverington & Maxwell [5] propose that many previously identified paleolakes in this region [3,4] are actually lava lakes, and the morphology of this delta is consistent with that interpretation.

True deltas: Terrestrial deltas are classified as fluvial-, wave-, or tide-dominated. On Mars, tidal influence is minimal [6], but wave energy over time is probably similar to that on Earth [7], so wave-dominated deltas are expected in large basins or in stormy climate regimes. Digitate margins of the best-preserved deltas studied so far indicate their fluvial domination [8]. River-mouth processes in a fluvial-dominated delta can be divided into inertial, buoyancy, and friction outflow [9,10]. The relative importance of each process depends on the rate of flow, amount of sediment and grain sizes, relative densities of effluent and ambient waters, and basin topography. These in turn depend mostly on the climate of the drainage region and its underlying geology and topography. Conversely, delta morphology places constraints on its climate regime.

Elongate deltas with relatively straight distributary channels form where inertial outflow dominates. In Aram Chaos, a long narrow fan-shaped deposit with long straight channels formed where a branch of Ares Vallis debouched into the basin (Figure 2). The narrow linear proportions of the delta reflect its deposition from high-velocity, inertia-dominated flow from a giant outflow channel.

Grain size is an important factor in shaping a delta, as seen in the classic arcuate shape of Gilbert deltas — coarse-grained, primarily inertial deltas formed by deposition from homopycnal (similar density) flow. Because the river water is nearly the same density as the lake water, mixing is rapid and thorough; suspended load and bed load both fall out close to the river mouths, giving the delta its characteristic steeply dipping foreset beds [9]. Several fan-shaped deposits have been previously identified as Gilbert deltas, including the Mangala Valles delta that we interpret as a lava delta [3,4,11].

In inertial deltas, hyperpycnal (high density) flow may also develop lateral to the main flow [9], causing turbidity currents and decreasing the angle of foreset beds up to 20% [12].

In a buoyancy river mouth, flow is hypopycnal (less dense than ambient water), and extends as a radially decelerating plume, dropping suspended load far into the basin [10,13] as in marine deltas on Earth, which have foreset beds with extremely shallow dips

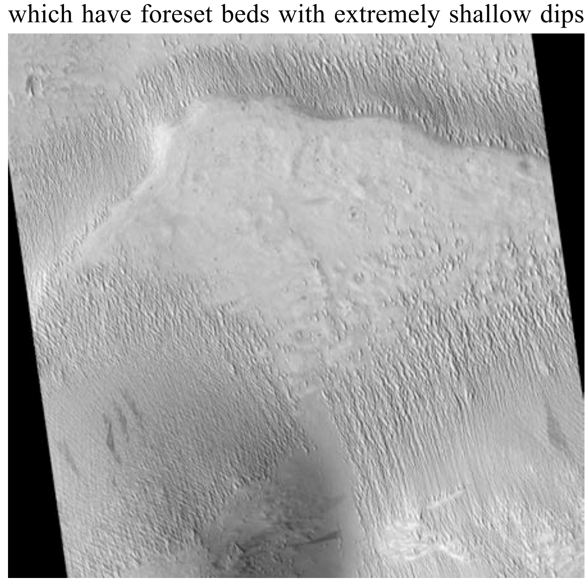

Figure 1. Probable lava delta in Mangala Valles, 6°S, 149°W. Image is ~5 km across, from MOC NA R05-02429.

(≤1°) [9]. Saline basin waters on Mars would also cause this type of flow.

Friction is important where a river enters a shallow-sloping basin. Inflow expands laterally, leading to bifurcating channels with triangular bars in the river mouths [10]. Friction-dominated deltas are very common on Earth [13], and on Mars may include the provisionally named "Eberswalde Crater" fan with its sinuous bifurcating channels [8,14-16].

Few deltas are completely dominated by one process. A beautifully preserved fan-shaped deposit in Aeolis Mensae (Figure 3) [15] is a good example of a delta that was created by a balance of processes. Measurements of channel sinuosity (to calculate flow velocity), and foreset bed angles (e.g. work by Lewis & Aharonson [16] at Eberswalde Crater), will put important constraints on the evolution of this delta. It is difficult to differentiate between processes in ancient deltas on Earth, because their plan views are buried [13], but on Mars, many are exposed, and may lead to insights about terrestrial deltas.

Other types of deltas. A fan delta forms where an alluvial fan enters a body of water [17], and are expected expected in an arid climate with lakes. Likely martian temperatures mean that ice will have been a factor in any body of water. Past glaciers should be evident in preserved landforms [23], such as kame deltas and grounding line wedges. A grounding line wedge or till delta (which forms where subglacial melt enters water beneath an ice shelf), was predicted [18] at the mouth of Ma'adim Vallis in Gusev Crater, but now seems unlikely, but if Lucchitta's [19] interpretation of outflow channels as analogous to Antarctic ice streams is correct, then grounding line wedges should be present on Mars. The distinctive feature of these deltas is that their top surface slopes slightly upward in the direction of flow, due to the pressure of the overlying ice shelf [20-22].

Glacial melting would produce kame deltas. Several features in polar regions resemble terrestrial kame-and-kettle topography [23,24], but no kame deltas have been explicitly identified. One promising location is eastern Darwin Crater, where others [4,25] have suggested the presence of glacial features.

Conclusions: Martian fan-shaped deposits must be examined for evidence of a tributary network, deltaic surface features, and other effects of flowing and standing water before they can confidently be called deltas. Analysis of the slopes of topset and foreset beds, planimetric forms, and shapes and dimensions of preserved channels and underlying basins will clues to depositional conditions, such as flow rates, relative densities, and constancy of flow, and these will help constrain martian climate history.

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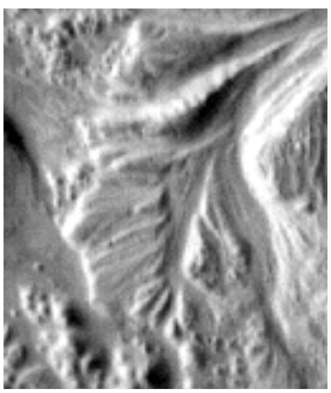

Figure 2. Distributary channels at the toe of the large inertial delta in Aram Chaos, near 3°N, 341°E. Image is ~1.6 km across, from THEMIS I10698012.

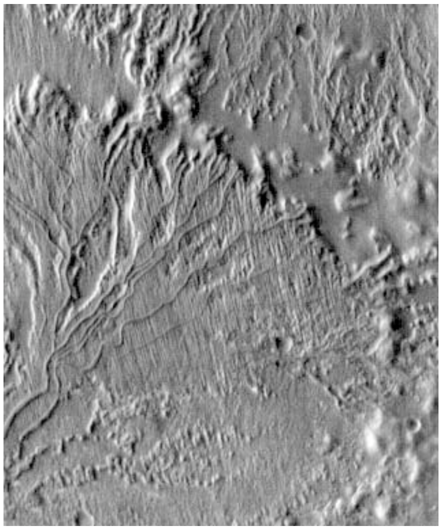

Figure 3. Fan in Aeolis Mensae, 6.5°S, 209°W. Primarily inertial, but with slightly sinuous bifurcated channels that indicate the contribution of frictional processes. Image is ~32 km across, from THEMIS I05588001.