THEATER-HEADED VALLEYS: THE ROLES OF OVERLAND FLOW AND GROUNDWATER SAPPING.
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Introduction: Significant differences are evident between most Martian valley networks and mature terrestrial watersheds [e.g., 1–4], providing useful constraints on the relative paleoclimate and/or hydrology of early Mars. Martian fluvial valleys often have irregular longitudinal profiles, low sinuosity, sparsely dissected or undissected areas between tributaries, steep sidewalls, and theater headscarps [1]. These features are similar to those of some headwater canyons in the Colorado Plateau of the southwestern United States (Fig. 1) [5,6]. Seepage springs often occur within alcoves near the base of headscarps, whereas fluvial incision of the plateau surface is limited (Fig. 1). The prevailing interpretation, which has not been quantitatively demonstrated, holds that overland flow is far less important than seepage in carving these valleys, so that erosion rates are slow and weathering-limited [5,6]. Laity and Malin [5] offered a qualitative model of lithology and structure that would favor groundwater sapping, based on a study of tributary canyons to the Colorado River in Utah. In their model, precipitation infiltrates from the plateau surface into sandstone aquifers, collects on less permeable interbeds, and emerges down-dip where a scarp exposes the interbed. These springs facilitate chemical and mechanical weathering of the headwall, undercutting of the alcove, and transport of wall debris. Fracture control of this groundwater flow influences the resulting valley network planform.

Figure 1. Shallow contributing streams above the head of the South Fork of Buck Canyon in Canyonlands National Park, Utah.

Figure 2. (a) Headscarp of Musselman Canyon, Utah. The arrow marks the contributing stream. Despite limited evidence of seepage, the headscarp has little debris relative to down-valley sidewalls shown in (b).

In October 2005, we conducted a preliminary field study of theater-headed valleys in Utah and Arizona to 1) determine whether the Laity and Malin sapping model is generally applicable to theater-headed valleys; 2) measure dimensions and gradients of ephemeral contributing streams that flow from the plateau surface over the valley headscarps (Fig. 2), to calculate overland discharge; and 3) examine a site that Howard had visited in 1985, where substantial erosion of vegetated alluvial fill has occurred near a valley headscarp within the past 20 years (Fig. 3). This work is necessary to test the common interpretation that theater-headed valleys on Earth and Mars are uniquely attributable to groundwater sapping, with minimal contributions from overland flow [e.g., 1,2].

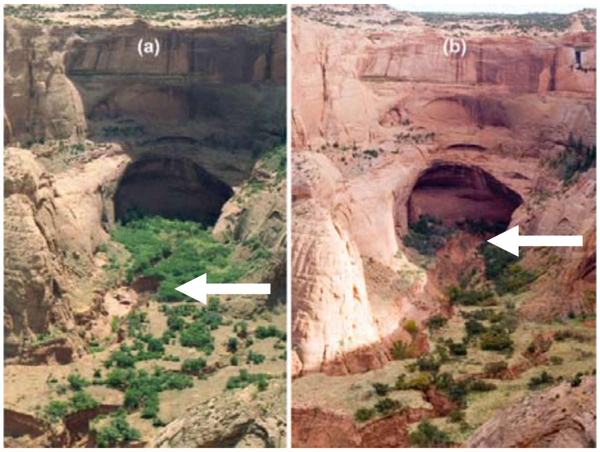

Figure 3. Tributary to Toenleshushe Canyon on the Navajo Reservation, Arizona. Note entrenchment of the vegetated alluvial fill (arrows) on the canyon floor between (a) 1985 and (b) 2005. The contributing stream enters the canyon above the letter b.

Observations: Satellite imaging, topography, and field observations show that contributing streams commonly flow over the headscarps of terrestrial theater-headed valleys (Figs. 1 and 2). In fewer cases both the plateau surface and strata dip away from a headscarp, so that no exterior water source is available, except runoff from the steep valley sidewalls.

Alcoves and active seepage springs occur in many of the theater headscarps that we visited, but the springs are often located on the upper half of the scarp, not always at the base where the Laity and Malin model places them. Vegetation is concentrated along the springs, where roots help to disaggregate the rock, but it is very sparse elsewhere on the scarps.

Some valleys are growing up-dip, where they can exploit perched aquifers as in the Laity and Malin model, but others are growing down-dip.

The theater heads are generally rounded in plan view, but some irregularities have formed in response to fracture patterns in the cap rock. The contributing streams have incised very shallow channels into the plateau, but the scarp faces are little modified where the stream overflows them. Debris is common along the canyon sidewalls but is largely absent from the base of the headwall (Fig. 2).

We measured the dimensions of two contributing alluvial channels, one on the plateau surface just above a theater headwall in Canyonlands National Park, Utah (Fig. 2), and one just below a headwall on the Navajo Reservation in northern Arizona. The Musselman Canyon channel (Utah) had a width=8.1 m, gradient=0.017, depth=0.23 m, and a contributing area of ~5 km^2. Depth was given by recent woody debris and sedimentation on the channel banks, and bed roughness was estimated at 0.03. Discharge was calculated using the Manning relationship at ~3 m^3/s, with runoff production ~0.2 cm/h at peak flow. The bed shear stress at this time was 38 N/m^2, which should be capable of transporting grains up to 6 cm in diameter, according to relationships established by Komar [7]. The largest rounded particle collected along this alluvial reach was 6 cm, confirming the model result.

In the Toenleshushe Canyon system (Arizona), the gravel supply is limited, and the alluvial channel is entrenched into thick, fine-grained alluvium on the floor of the bedrock canyon. Channel width was ~9.1 m, but the greater flow depth of 0.375 m resulted in a discharge estimate of 6 m^3/s, or peak runoff production of 2 cm/hr from the 1 km^2 contributing area. Swept vegetation, woody debris, and bank erosion controlled this depth estimate. In a neighboring canyon, entrenchment of the vegetated alluvial fill has advanced up to the canyon headwall within only 20 years (Fig. 3), requiring more rapid erosion than would likely be possible from groundwater acting alone.

Discussion: The lithology and structure of theater-headed valleys show a diversity that is not well represented in the idealized Laity and Malin model [5]. Contributing overland streams cannot be neglected in the interpretation of these canyons, as the streams are capable of significant sediment transport and bed abrasion given reasonable precipitation. Arid zone rainfall is often localized, and peak discharges for small watersheds are often similar to those of humid regions, although the recurrence intervals are much longer [8]. The relative roles of overland flow and groundwater remain to be determined, but in the canyons we visited, the latter appears to be more important in weathering than in erosion. The rounded valley headscarps suggest mass wasting that is facilitated by fluvial erosion of the base of the headscarp. Detailed studies of more theater-headed valleys with and without contributing streams are necessary to validate general arguments regarding the origin of such valleys on Earth and Mars.

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