ORIGIN OF THEATER-HEADED TRIBUTARIES TO ESCALALANTE AND GLEN CANYONS, UTAH.

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Introduction: Theater-headed tributary canyons to the Escalante and Colorado Rivers in Glen Canyon National Recreation Area, Utah, have been cited as important analogs to fluvial valleys on Mars [1–4] (Fig. 1). These canyons have overhanging headwalls up to 200 m high, near-vertical sidewalls, and roughly constant widths (Fig. 1). Alcoves with active seeps or salt weathering are common in the headwall and sidewalls (Fig. 2). These tributaries dissect the lower Jurassic Navajo Formation, a cross-bedded aeolian sandstone with thin lenses of impermeable finer-grained sediments. The canyon floors are interbedded fluvial sandstones and shales of the underlying Kayenta Formation [3]. The study area occurs on the southwest-dipping limb of Waterpocket Fold (surveyed strike 131° dip 1.4° in East Bowns Canyon). Lake Powell was 33 m below full level in March, 2008.

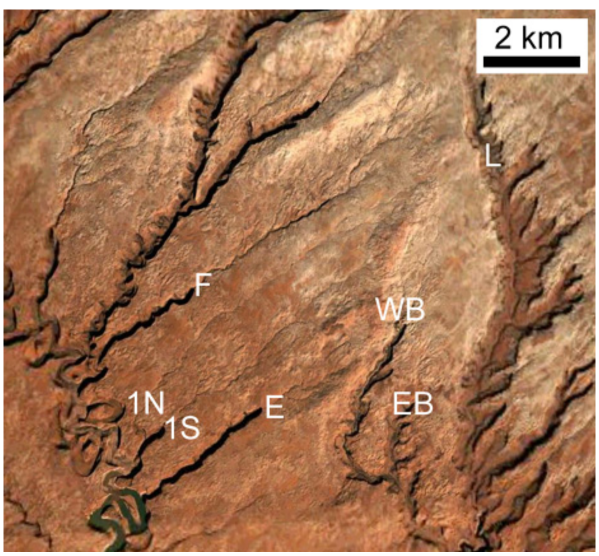

Fig. 1. Study area including Fence (F), Explorer (E), 1N/1S, West Bowns (WB), East Bowns (EB), and Long (L) Canyons.

Laity and Malin [1,2] studied this area in the early 1980s, concluding that these tributary canyons primarily result from seepage weathering (several processes of chemical and physical breakdown) at the base of the headwall and seepage erosion (transport of the resulting debris by the small spring-fed stream), collectively termed groundwater sapping. They viewed runoff from the contributing watershed as minor due to high permeability of fractured Navajo sandstone. In March and May of 2008, we visited these canyons to re-evaluate the roles of seepage and overland flows in weathering and sediment transport.

Fig. 2. Fence Canyon headwall. Note incised contributing stream, alcove, seep, plunge pool swept clear of debris, and vegetated floor. Relief is ~150 m.

Observations: We examined the valley floor, the base of the headwall, and the contributing plateau at Explorer Canyon, two branches of a smaller unnamed tributary to its north (here called 1S and 1N) (all are tributaries to the Escalante River, which joins the Colorado in Glen Canyon/Lake Powell), and two branches of Bowns Canyon (which drains directly to Lake Powell). We also surveyed the Fence Canyon headwall from the plateau surface and small branches of Iceberg and Long Canyons from the canyon floor and plateau, respectively (Fig. 1). Collected data include spring pH, hardness, and discharge (to evaluate the spring's capacity to weather and erode the headwall rock); compressive strength by Schmidt hammer [5] of Navajo and underlying Kayenta beds (to determine whether vertical strength differences facilitate undercutting of the headwall); Selby [6] bulk strength of Navajo sandstone (to evaluate the effect of joints on headwall strength); discharge estimates for flash floods and size of transported rocks (to compare the erosional capacity of floods with spring-fed streams); and vertical profiles of valley headwalls and alcoves using a laser rangefinder (to quantify morphology and evaluate factors that may influence alcove development).

Compressive strength and Selby index. Schmidt hammer rebound (R) values in the Navajo Formation are moderate (R~45, or ~50 N/mm^2 compressive strength) on both wet and dry scarps, but lower on weathered plateau surfaces with small sheeting joints within a few centimeters of the surface. Seepage weathering affects only the first cm or so of the surface, and most of the resulting small debris is easily broken down and transported [1,2]. Selby values for headwall rock strength are high (~90) due to the moderate R-values, wide spacing and horizontal/vertical orientations of joints (or absence thereof), discontinuity of joints, and small joint width [6].

Headwalls. Headwalls typically include an alcove and a less-weathered, sheet-fractured face above it (Fig. 2). Thin impermeable lenses or highly permeable interbeds may concentrate seepage at multiple levels. Alcoves were not observed in theater headwalls with large vertical joints oriented perpendicular to the face, but shallow sheeting joints are common. Different weathering processes predominate on different sections of the headwall relief. Above canyon headwalls, contributing overland streams incised narrow, V- to U-shaped slot canyons, which funnel ephemeral waterfalls over the headwall that form a small plunge pool at its base. The lower part of the alcove contains talus and may be vegetated if there is spring discharge. Seeps issue from the most recessed areas of all of the observed headwall alcoves, but not all of the sidewall alcoves, which may have formed mostly during wetter pluvial epochs. The scarp is less weathered above alcoves, suggesting that stress-release fracturing is required for headwall retreat in that zone.

Springs, flash floods, and channels. Measured discharges of spring-fed streams varied between 0.001 and 0.002 m^3/s. Previous flash floods have formed channels up to >10 m wide and >1 m deep and have transported imbricated rocks at least tens of cm in size. Peak discharges estimated using the Manning relationship are ~1–10 m^3/s near headwalls and three orders of magnitude higher than spring flows. During rainfall observed in East Bowns Canyon from the evening of May 21 through the morning of the 22nd, 2008, runoff occurred almost immediately from slickrock surfaces bounding the canyon.

Spring-fed streams are much smaller than the channels that they occupy and play little role in sediment transport. Stream beds are dominantly exposed bedrock or covered with vegetation that is watered by the small stream. This vegetation inhibits sediment transport through the canyon, but spring flow may weather the bed and facilitate erosion during floods.

Structural and topographic influences on valley planform. Large tectonic joints are uncommon to absent in the studied valley headwalls, and stress-release fractures down-canyon are usually parallel to the walls and most evident in promontories. Smaller intersecting joints on some weathered plateau surfaces do not appear to penetrate deeply, based on examination of scarps, but they locally influence channel incision.

The studied Escalante River tributaries are growing up the contributing dip slope, which influences both their runoff and groundwater supply. However, Bowns and Long Canyons are growing along strike, tracking up their entrenched contributing streams rather than the aquifer dip. The canyon orientation is predominantly topographic rather than structural. Some alcoves are growing in the down-dip direction.

Discussion: Seepage erosion is a negligible sediment transport process within the canyons, relative to flash floods supplied from slickrock surfaces. Seepage weathering depends on flash floods to remove debris from the headscarp, thus the canyons grow headward along the incised contributing streams and not necessarily up major tectonic fractures or the structural dip. Alcove development depends largely on the massive, unjointed nature of the Navajo sandstone; otherwise the roof would collapse, and the waterfall could directly attack the base of the headscarp. It is unknown whether bedrock in the Martian highlands was competent enough for similar cavities to develop.

Observations suggest a hybrid model for these theater-headed valleys involving seepage weathering at the headwall base, transport of resulting debris and incision of the contributing and canyon-interior streams by flash floods, and structural responses to valley incision. Theater-headed valleys in Navajo sandstone do not provide empirical support for models of valley network formation on Mars without surface runoff.

References: [1] Laity J. E. (1983) *Phys. Geogr.*, *4*, 103–125. [2] Laity J. E. and Malin M. C. (1985) *Geol. Soc. Amer. Bull.*, *96*, 203–217. [3] Howard A. D. et al. (eds.) *Sapping Features of the Colorado Plateau*, NASA Spec. Pub. 491. [4] Higgins C. G. and Coates D. R. (eds.) *Groundwater Geomorphology*, Geol. Soc. Amer. Spec. Pap. 252. [5] Goudie A. S. (2006) *Prog. Phys. Geogr.*, *30*, 703–718. [6] Selby M. J. (1980) *Zeitschrift fur Geomorphologie*, *21*, 1–13.