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Origin and development of theater-headed valleys in the Atacama Desert, northern Chile: Morphological analogs to martian valley networks

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ABSTRACT

Understanding planetary landforms, including the theater-headed valleys (box canyons) of Mars, usually depends on interpreting geological processes from remote-sensing data without ground-based corroboration. Here we investigate the origin and development of two Mars-analog theater-headed valleys in the hyperarid Atacama Desert of northern Chile. Previous workers attributed these valleys to groundwater sapping based on remote imaging, topography, and publications on the local geology. We evaluate groundwater sapping and alternative hypotheses using field observations of characteristic features, strength measurements of strata exposed in headscarps, and estimates of ephemeral flood discharges within the valleys. The headscarps lack evidence of recent or active seepage weathering, such as spring discharge, salt weathering, alcoves, or vegetation. Their welded tuff caprocks have compressive strengths multiple times those of the underlying epiclastic strata. Flood discharge estimates of cubic meters to tens of cubic meters per second, derived using the Manning equation, are consistent with the size of transported clasts and show that the ephemeral streams are geomorphically effective, even in the modern hyperarid climate. We interpret that headscarp retreat in the Quebrada de Quisma is due to ephemeral flood erosion of weak Miocene epiclastic strata beneath a strong welded tuff, with erosion of the tuff facilitated by vertical jointing. The Quebrada de Humayani headscarp is interpreted as the scar of a giant landslide, maintained against substantial later degradation by similar strong-over-weak stratigraphy. This work suggests that theater-headed valleys on Earth and Mars should not be attributed by default to groundwater sapping, as other processes with lithologic and structural influences can form theater headscarps.

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1. Introduction

The martian landscape has compelling analogs in both hot and cold deserts on Earth, particularly in very arid regions with little recent erosion by surface water (e.g., Chapman, 2007). The preservation of ancient cratered terrain in the southern highlands shows that Mars has been hyperarid for about 75% of its history, although it experienced wetter conditions at least intermittently prior to about 3.0–3.6 Ga (e.g., Malin, 1976; Carr and Clow, 1981; Golombek et al., 2006; Fassett and Head, 2008; Grant and Wilson, 2011). The highlands contain fluvially degraded impact craters and branching valley networks, most of which drained to enclosed basins (e.g., Maxwell and Craddock, 1995; Craddock et al., 1997). Most fluvial valleys are incised ~50–350 m into sparsely dissected intercrater geomorphic surfaces that formed during the Middle to Late Noachian Epochs (Howard et al., 2005). On these intercrater surfaces, martian fluvial valleys commonly have a theater-shaped headscarp and steep sidewalls with relatively little dissection by gullies (e.g., Pieri, 1980). Valley cross sections are locally V-shaped (particularly on steeper regional slopes, e.g., Fig. 1) but more commonly are trapezoidal, with a flat floor (Baker and Partridge, 1986; Goldspiel et al., 1993; Williams and Phillips, 2001).

By analogy with some morphologically similar theater-headed valleys (box canyons) on Earth, many workers have attributed these characteristics to groundwater sapping, a term that encapsulates seepage-related weathering processes and erosion of the resulting debris by spring discharge (e.g., Pieri, 1980; Mars

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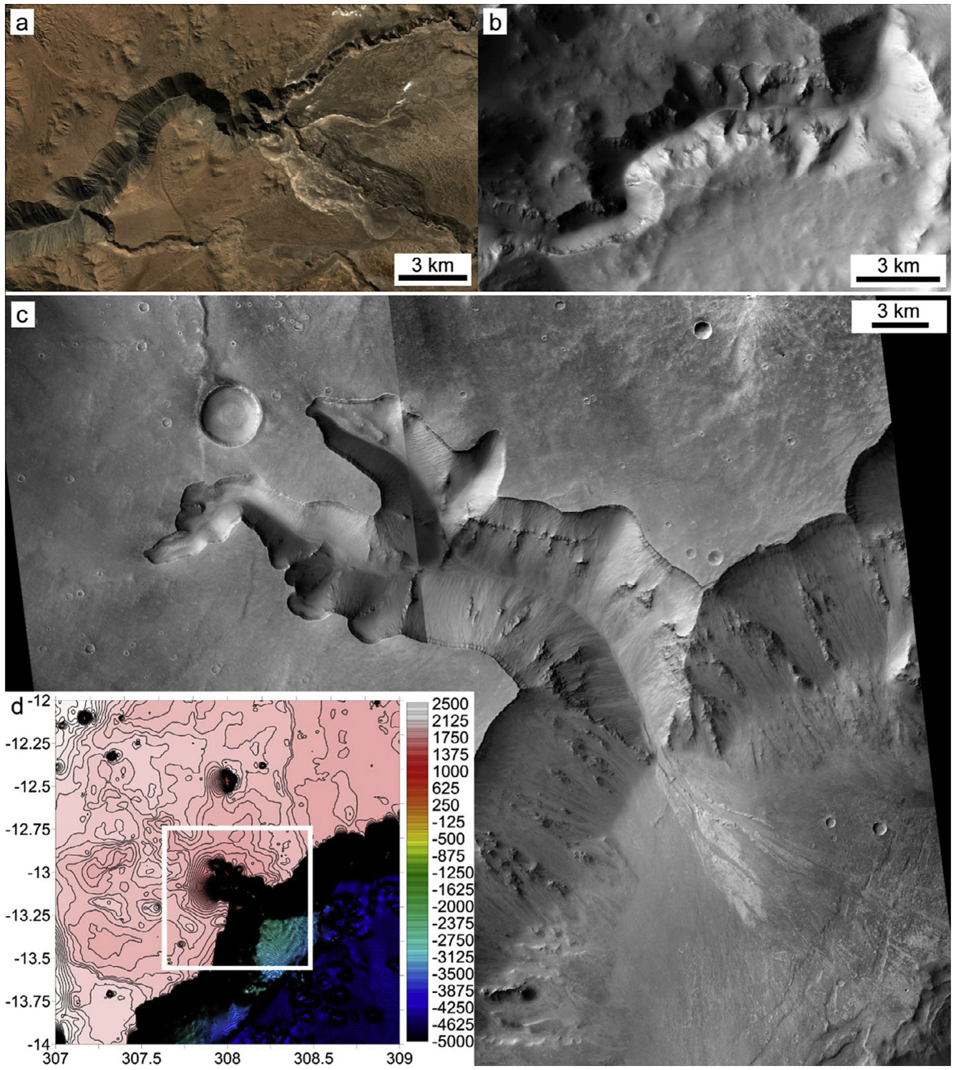

Fig. 1. Comparison of (a) Quebrada de Tiliviche (19.5°S, 70.5°W, Google Earth, flow toward the left) with (b) a martian fluvial valley (5.4°S, 134.7°E, Mars Reconnaissance Orbiter Context Camera, flow toward the right). In both cases, note the deeply incised valley and poorly dissected interfluve areas. (c) Theater-headed valleys in the Valles Marineris region of Mars, 13.2°S, 51.9°W, provided for comparison with the smaller Quebrada de Quisma in Fig. 5a. Mars Reconnaissance Orbiter Context Camera images P08_004027_1645 and P15_006796_1649. (d) Mars Orbiter Laser Altimeter topography (25 m contour interval) of the area shown in Fig. 1c (white outline) and surroundings. Note the plateau slope toward the valley heads. North is up in this and all subsequent plan view figures.

Channel Working Group, 1983; Brakenridge, 1990; Malin and Carr, 1999; Harrison and Grimm, 2005). Laity and Malin (1985, p. 203) defined groundwater sapping as "the process leading to the undermining and collapse of valley head and side walls by weakening or removal of basal support as a result of enhanced weathering and erosion by concentrated fluid flow at a site of seepage." On Earth, seepage weathering can enable retreat of a vertical headscarp by undermining of the base, through processes including physical weathering (e.g., salt weathering or freeze thaw), chemical weathering, or root growth at a seepage face. Spring discharge and/or surface runoff are invoked as the processes that remove the weathered debris and any mass-wasted materials (Dunne, 1980; Laity, 1983; Higgins, 1984; Laity and Malin, 1985; Howard et al., 1988). If valley weathering and erosion by spring discharge alone were possible under a cold, arid climate, then the groundwater sapping interpretation could have significant implications for the paleoclimate of early Mars (e.g., Gaidos and Marion, 2003).

Interpretations of groundwater sapping on Mars have been controversial, however, as dissection on Mars is locally dense (e.g., Hynek and Phillips, 2003; Mangold et al., 2004) and many tributary heads occur near drainage divides (e.g., Masursky et al., 1977; Craddock and Howard, 2002; Carr, 2002). For both of these reasons, available contributing aquifers would have been small. In addition, significant aquifer recharge would have been needed to transport the weathered volume of debris equivalent to martian valley volumes (Howard, 1988; Gulick and Baker, 1990; Goldspiel and Squyres, 1991; Goldspiel et al., 1993; Grant, 2000; Gulick, 2001; Craddock and Howard, 2002). Alternative explanations for steep or vertical valley headscarps in terrestrial bedrock have been noted, including surface flood erosion of strong-over-weak stratigraphy or vertically jointed rock, although very large floods ('megafloods') may be required to topple columns of jointed rock (Lamb et al., 2008a, 2014; Lamb and Dietrich, 2009). Flood erosion of strong-over-weak stratigraphy can involve undercutting of the headscarp caprock at or around waterfall plunge pools (e.g., Lamb et al., 2006, 2007). The latter studies suggest that a groundwater sapping origin of bedrock valleys may not have been uniquely demonstrated anywhere on Earth, and that a positive relationship between spring discharge and weathering rate similarly lacks empirical support. However, groundwater sapping in unconsolidated materials has been demonstrated in the laboratory (Howard and McLane, 1988; Marra et al., 2014) and in at least one