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Did the martian outflow channels mostly form during the Amazonian Period?

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ABSTRACT

Simud, Tiu, and Ares Valles comprise some of the largest outflow channels on Mars. Their excavation has been attributed variously to (or a combination of) erosion by catastrophic floods, glaciers, and debris flows. Numerous investigations indicate that they formed largely during the Late Hesperian (3.61–3.37 Ga). However, these studies mostly equate the ages of the outflow channel floors to those of the flows that generated mesoscale (several hundred meters to a few kilometers) bedforms within them. To improve the statistical accuracy in the age determinations of these flow events, we have used recently acquired high-resolution image and topographic data to map and date portions of Simud, Tiu and Ares Valles, which are extensively marked by these bedforms. Our results, which remove the statistical effects of older and younger outflow channel floor surfaces on the generation of modeled ages, reveal evidence for major outflow channel discharges occurring during the Early (3.37–1.23 Ga) and Middle (1.23–0.328 Ga) Amazonian, with activity significantly peaking during the Middle Amazonian stages. We also find that during the documented stages of Middle Amazonian discharges, the floor of Tiu Valles underwent widespread collapse, resulting in chaotic terrain formation. In addition, we present evidence showing that following the outflow channel discharges, collapse within northern Simud Valles generated another chaotic terrain. This younger chaos region likely represents the latest stage of large-scale outflow channel resurfacing within the study area. Our findings imply that in southern circum-Chryse the martian hydrosphere experienced large-scale drainage during the Amazonian, which likely led to periodic inundation and sedimentation within the northern plains.

1. Introduction

The southern circum-Chryse Simud, Tiu, and Ares Valles (Fig. 1a) comprise some of the largest outflow channels on Mars, and their excavation has been attributed to erosion by catastrophic floods (Baker, 1982, 2009a, 2009b; Komatsu and Baker, 1997; Rodriguez et al., 2014), glaciers (Lucchitta, 1982, 2001; Pacifici et al., 2009; Rodriguez et al., 2014), CO_2-charged debris flows (Hoffman, 2000), H_2O-charged debris flows (Nummedal and Prior, 1981; Tanaka, 1999; Rodriguez et al., 2006a), and/or lava flows (Schonfeld, 1976; Leverington, 2011; Hopper and Leverington, 2014). The analyses of Viking Orbiter era geochronologies led to a consensus that the Late Hesperian (3.61–3.37 Ga, (Werner and Tanaka 2011; Michael 2013)) comprised a period characterized by major hydrologic resurfacing on Mars, which resulted in the formation of the planet's major outflow channel systems (Scott and Tanaka, 1986; Rotto and Tanaka, 1995; Tanaka, 1997). Nevertheless, this view was occasionally disputed by a few contemporaneous investigations (Kargel et al., 1995; Cabrol et al., 1999). Catastrophic floods released via the southern circum-Chryse outflow channels are thought to have played a key role in the formation of oceans in planet's northern lowlands

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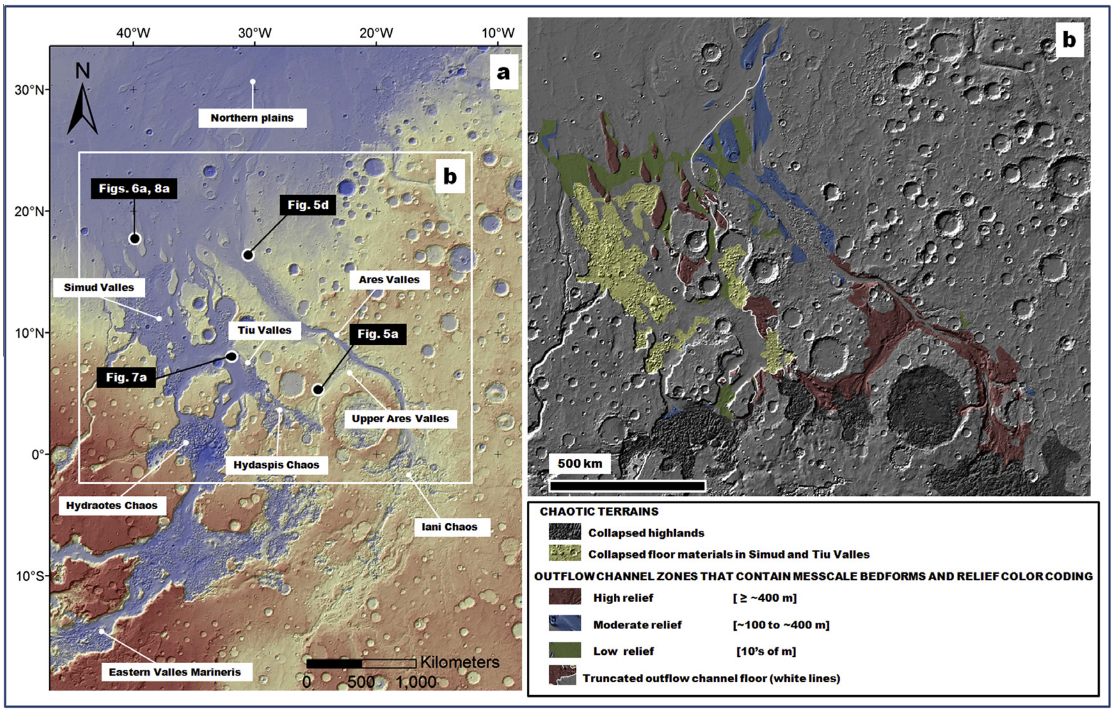

Fig. 1. (a) View of southern circum-Chryse providing regional geograp areas. The black dots show the center locations of Figs. 5a, 5d, 6a, 7a and 8a. [MOLA DEM (Digital Elevation Model), 128 pixels per degree]. (b) Geomorphologic map depicting (1) floor sections within Simud, Tiu, and Ares Valles that retain large outcrops marked by surface flow morphologies and (2) extensive chaotic terrains within and adjoining these outflow channels. [MOLA-shaded relief forms the map base, 128 pixels per degree].

(Parker et al., 1989; Clifford and Parker, 2001; Fairén et al., 2003). Thus, understanding the ages of these flooding events comprises an aspect of fundamental importance in martian paleohydrology.

The availability of recently acquired higher resolution post-Viking Orbiter image and topographic datasets has resulted in renewed investigations that also challenge the view of a Hesperian-dominated history of outflow channel formation. For example, some investigations show evidence indicative of regional outflow channel formation during the Late Noachian (Warner et al., 2013a) and Early Amazonian (Rodriguez et al., 2011; Warner et al., 2013b). In a more recent study, Rodriguez et al. (2014) investigated outflow channel exposures in southern circum-Chryse containing decameter-scale bedforms indicative of Middle Amazonian outflow channel formation associated with glaciation and catastrophic flooding events. Although these new investigations indicate a significant deviation from the putative, almost exclusive Late Hesperian age benchmark of outflow channel activity in circum-Chryse, this view still remains ingrained in Mars science literature (Coleman et al., 2007).

Using a Mars Reconnaissance Orbiter (MRO) Context (CTX, Malin et al., 2007) image mosaic of Simud, Tiu, and Ares Valles (5.15–5.91 m/pixel) in combination with the analysis of a regional Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA, Zuber et al., 1992) gridded digital elevation model ($\sim$460 m/pixel horizontal and $\sim$1 m vertical resolution), we produced a comprehensive geomorphic map of channel floor surfaces within Simud, Tiu and Ares Valles that are extensively marked by assemblages of well-preserved mesoscale (several hundred meters to a few kilometers) bedforms (Fig. 1b). We colorcoded the mapped floors based on the relief ranges of the most prominent bedform morphologies they contain (Fig. 1b), which serves as a proxy for the magnitude of upper crustal erosion produced by the related flow events.

We have used impact crater statistics to determine the ages of the flows that produced the mapped floors (Figs. 2 and 3 and supplementary material). Although these surfaces are characterized by the widespread occurrence of bedforms, they do exhibit a significant degree of complexity when examined at local scales, which needs to be considered to produce precise age estimates. In particular, they include zones where the bedforms appear significantly destroyed by collapsed terrains or widely covered by sedimentary mantles (e.g., Fig. 4). In addition, there are also some older terrains within these outflow channel floor surfaces that were not noticeably resurfaced by the flow events that produced the mapped mesoscale bedforms (e.g., Fig. 4). These older surfaces could represent tectonic down-dropping associated with losses of buried volatiles before the outflow channel floods, or they could represent very ancient flood events, where the bedforms have been destroyed. Thus, to maximize the statistical accuracy of our modeled ages, we carefully avoided counts within these types of surfaces, which clearly predate or post-date their bedform assemblages. The dated surfaces are located downstream from the various initiation zones of the mapped floors (Fig. 2a), and so their distribution is optimal to establish an improved chronology of outflow channel discharge events.

Our approach significantly differs from that used in previous investigations based on Viking Orbiter image data. Due to the data's significantly lower resolution, the modeled ages were obtained using impact crater counts distributed throughout the entire outflow channel floors (Scott and Tanaka, 1986; Rotto and Tanaka, 1995; Tanaka, 1997). Similarly, the much broader mapping scale (1:20,000,000) implemented in the global map by Tanaka (2014), which has resulted in a considerably improved global geochronology of Mars, did not permit the recognition of the outflow channel terrain types we have mapped.

2. Impact crater statistics methodology

We estimated the mapped outflow channel surface ages using crater statistics analyzed with *CraterTools* (Kneissl et al., 2011) and *Craterstats* (Michael and Neukum, 2010; Michael et al., 2012) following the description presented in Platz et al. (2013). We mapped all craters down to 100 m in diameter. Currently, for