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Simulating the development of Martian highland landscapes through the interaction of impact cratering, fluvial erosion, and variable hydrologic forcing

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Abstract

On the highlands of Mars early in the history of the planet precipitation-driven fluvial erosion competed with ongoing impact cratering. This disruption, and the multiple enclosed basins produced by impacts, is partially responsible for a long debate concerning the processes and effectiveness of fluvial erosion. The role of fluvial erosion in sculpting the early Martian landscape is explored here using a simulation model that incorporates formation of impact craters, erosion by fluvial and slope processes, deposition in basins, and flow routing through depressions. Under assumed arid hydrologic conditions, enclosed basins created by cratering do not overflow, drainage networks are short, and fluvial bajadas infill crater basins with sediment supplied from erosion of interior crater slopes and, occasionally from adjacent steep slopes. Even under arid conditions adjacent crater basins can become integrated into larger basins through lateral erosion of crater rims or by rim burial by sediment infilling. Fluvial erosion on early Mars was sufficient to infill craters of 10 km or more in diameter with 500–1500 m of sediment. When the amount of runoff relative to evaporation is assumed to be larger, enclosed basins overflow and deeply incised valleys interconnect basins. Examples of such overflow and interconnection on the Martian highlands suggest an active hydrological cycle on early Mars, at least episodically. When fluvial erosion and cratering occur together, the drainage network is often disrupted and fragmented, but it reintegrates quickly from smaller impacts. Even when rates of impact are high, a subtle fluvial signature is retained on the landscape as broad, smooth intercrater plains that feature craters with variable amounts of infilling and rim erosion, including nearly buried "ghost" craters. The widespread occurrence of such intercrater plains on Mars suggests a strong fluvial imprint on the landscape despite the absence of deep, integrated valley networks. Indisputable deltas and alluvial fans are rare in the crater basins on Mars, in part because of subsequent destruction of surficial fluvial features by impact gardening and eolian processes. Simulations, however, suggest that temporally-varying lake levels and a high percentage of suspended to bedload supplied to the basins could also result in poor definition of fan–delta complexes.

Keywords: Mars; Fluvial; Simulation; Crater; Hydrology; Landform

1. Introduction

In this paper modeling of erosional and depositional features on the ancient highlands of Mars is discussed in the context of the competition between impact cratering and fluvial erosion, and its relationship to the concept of

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geomorphic complexity. As with most abstract concepts, complexity as applied to surface processes can be attributed to a wide range of possible process–response interactions. One type of complexity occurs when relatively constant process forcing produces temporally complicated responses, such as stream meandering (Ikeda et al., 1981; Howard, 1991; Howard, 1996; Sun et al., 2001), stream braiding and avulsion (Murray and Paola, 1994, 1997; Sun et al., 2002), cyclic erosional steps (Parker and Izumi, 2000; Sun and Parker, 2005), epicycles of arroyo cutting and filling (Bull, 1997), and mass wasting on steep slopes characterized by weathering to form regolith interrupted by episodic removal by rapid mass wasting (White, 1949). Another type of complexity occurs when gradual spatial or temporal changes in the intensity or pattern of forcing produce discontinuous responses or thresholds (Schumm, 1973, 1979), such as geomorphic thresholds in sediment transport (i.e., the critical shear stress), gullying (Howard, 1999; Tucker et al., 2006), some types of landslides, and changes of bed type in stream channels (Howard, 1980). Another type of complexity occurs when the "normal" mode of functioning of a geomorphic system is interrupted by episodic high-magnitude forcing, such as large precipitation events, volcanic eruptions, and direct and indirect effects of earthquakes, so that transient geomorphic responses are triggered. The type of complexity discussed here is of the latter case, where the relatively continuous development of fluvial drainage networks is episodically interrupted by impact craters, resulting in a landscape that is in perpetually transient evolution. A subset of cratering–fluvial interactions is also examined where a landscape formed by multiple impacts serves as the initial condition for subsequent fluvial erosion, with the attendant complication of multiple enclosed basins that may or may not be hydrologically connected.

Perhaps the most universal cause for complex patterns of landform evolution is where multiple processes affect the landscape with nearly equal magnitude, particularly if one of the processes is episodic but of high magnitude (as is the case with impact cratering). On Earth, tectonic deformation often causes disruptions of geomorphic systems by creating relief, altering drainage paths, warping stream profiles, and, through earthquakes, causing rapid earth movements (e.g., Burbank and Pinter, 1999; Schumm, 2000; Summerfield, 2000; Burbank and Anderson, 2001; Schumm, 2005). On the other two Solar System bodies that have demonstrably experienced fluvial erosion (Mars and Titan) tectonic deformation has been modest during the periods of fluvial activity, but cratering has played much the same role in creating relief and disturbing fluvial systems.

The origin and formative environment for fluvial landforms on the ancient cratered terrain on Mars (Fig. 1) has been debated since the first global image was provided by Mariner 9 in the early 1970s. These images

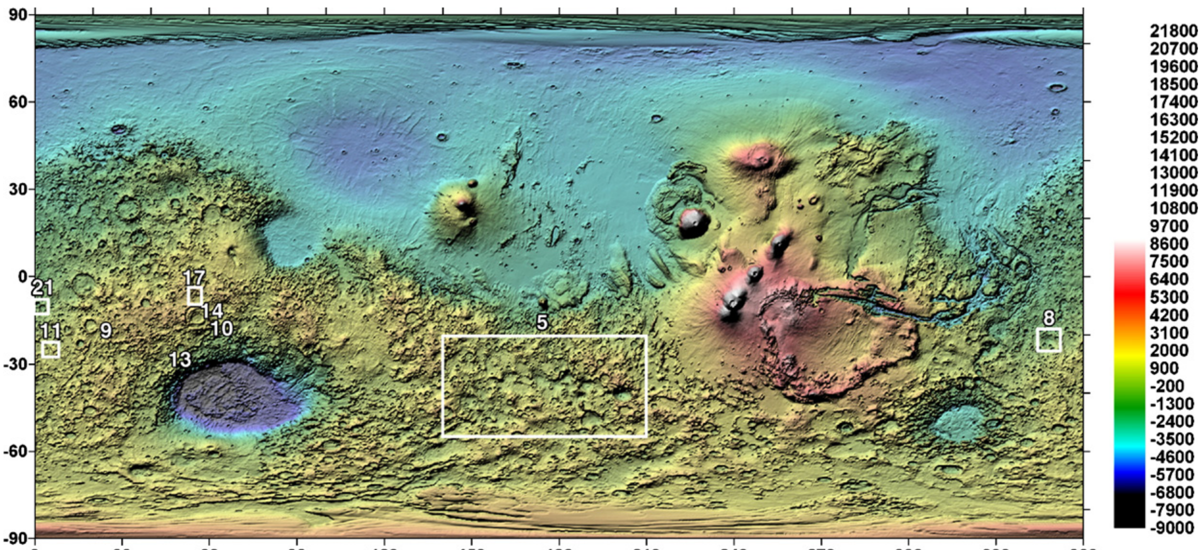

Fig. 1. Elevation-cued shaded relief map of Mars showing location of figures. Latitudes and east longitudes are labeled. Boxes shown only for images of larger regions. Elevations in meters relative to Martian datum. The ancient cratered highlands occupies the southern half of the map, and features the large impact basins Hellas (left side) and Argyre (right side). The Tharsis volcanic province spans the equatorial latitudes in the longitude range from 210°E to 310°E. The northern lowlands at the top of the image is a younger surface mantled in sediment and volcanic flows.