MARTIAN GEOLOGIC "REVOLUTIONS": A TALE OF TWO PROCESSES;
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The antiquated geologic term "revolution" is defined as "A term formerly popular among geologists for a time of profound orogeny and other crustal movements, on a continentwide or even worldwide scale, the assumption being that such revolutions produced abrupt changes in geography, climate, and environment" [1]. The term is little used today because of changes in our definition of "orogeny" and in our understanding of Earth's geologic history. Herein, I informally resurrect the term for Mars, in modified form, because of its suitability to this planet. My definition is "a time of profound geologic activity resulting in global changes in physiography, climate, or environment."

On Earth, most surface rocks (except the youngest) record a cumulatively complex geologic history, and their landscapes are largely molded by surficial processes. On Mars, however, structure and topography are more directly the results of volcanism and tectonism. Singular, major volcanic and tectonic events dominated in shaping the surface, and they strongly influenced the planet's environment. Impact cratering has also had a major role in the geology of Mars, and geologic revolutions related to cratering events may be proposed. However, here I examine only those revolutions apparently or possibly related to volcanism and tectonism, because I am reviewing the thrust of work from NASA's research project "Mars: Evolution of Volcanism, Tectonism, and Volatiles."

Below I outline three possible revolutions on Mars that are based on geologic evidence. Each includes uncertainties in such fundamental aspects as origin, nature and sequence of events, and environmental significance. Activity of the revolutions overlapped somewhat because of their longevity and planetwide effects. Nevertheless, the concept that revolutions have dominated the surface history of Mars provides a context for evaluating individual geologic events and the interrelation of geologic forces with climate and environment.

(1) Plate tectonics and the northern lowlands. Researchers have advocated either impact [2, 3] or tectonic origins [4, 5] for the northern lowlands (which cover about 40% of Mars), and this controversy will likely continue until more definitive data are gathered. Geologic observations and inferences consistent with a plate-tectonic origin [6] include (a) the lowering of a broad section of the crust (possibly through isostatic adjustment of a thinned crust [4]); (b) the possibility that Phlegra Montes (a north-trending ridge complex more than 1,000 km long and about 1,000 km northeast of Elysium Mons) are an extinct spreading center (suggested by their elevation, spreading-ridge morphology, and central location in the northern lowlands); and (c) the appropriate position and orientation of Tharsis Montes for arc-type volcanism relative to Phlegra Montes. Phlegra Montes were heavily degraded during the Late Noachian [7], indicating that any associated volcanic and tectonic activity had ceased by then. If further analysis confirms a tectonic hypothesis, this revolution accounts for major topographic modification of nearly one Martian hemisphere.

(2) Tharsis tectonism and filling of lowlands. The Tharsis rise is a complex of tectonic centers that include Tharsis Montes, Syria Planum, Claritas Fossae, the Thaumasia rise, Valles Marineris, Tempe Terra, Alba Patera, and Ceraunius Fossae. It largely developed during Noachian and Hesperian time [8]. Systems of near- to far-ranging radial and concentric grabens formed concomitantly with development of topographic highs [9]. During the Late Noachian and Early Hesperian [8], wrinkle ridges were formed concentric to the Tharsis rise and more than 2,000 km away from its center. The rise and its associated structures stretch out over a hemisphere of the planet. Two profound effects may have resulted from the uplift: (a) the uncompensated mass distribution of the planet

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may have been significantly altered [10], which may have resulted in polar wandering [11] and temporarily high obliquity [12] that changed ice-frost depositional environments [13, 14]; and (b) the probable formation of a broad zone of increased hydraulic potential in the ground-water system [15]. Fault activity, earthquakes, and volcanic heating associated with the rise caused breakouts of debris flows and catastrophic floods that carved the outflow channels of Chryse Basin and Mangala Valles [15-17]. These discharges contributed to extensive erosion of large highland areas, resurfacing of much of the northern plains [18], and a major redistribution of the planet's ground water (some likely ended up in the polar caps).

(3) Centralization of volcanism at Tharsis and Elysium. By the end of the Early Hesperian, Martian volcanism had changed dramatically. Previously, it had dispersed over the planet fields of broad, simple lava flows originating from fissures (minor central, dominantly pyroclastic volcanism was probably produced by phreatomagmatic eruptions). Now, volcanism began to produce regional fields of elongate, lobate flows and to build large shields or fissure complexes at Tharsis and Elysium [19, 20]. These changes could have resulted from general cooling and thickening of the lithosphere that decreased the magma supply rate [19] and from pronounced hydrothermal circulation that drove away ground water from eruptive centers. Possible related effects of centralized volcanism include (a) further changes in the planet's uncompensated mass distribution, with consequences as noted above; (b) continued discharge of ground water at the peripheries of volcanotectonic rises; and (c) strong localization of heat flow, which would have affected the form of the cryosphere and possibly decreased planetwide small-valley formation by sapping during the Early Hesperian [21].

We are fortunate that the surface of Mars, unlike surfaces of most other photographed bodies in the Solar System, so richly and straightforwardly reflects both the long-term geologic and the environmental histories of the planet. We can thus identify and postulate revolutionary events in Martian volcanic and tectonic history that produced profound changes in the planet's orientation, physiography, climate, ground and surface volatile distributions, and heat flow.

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