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Sequence and timing of conditions on early Mars

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ABSTRACT

The geological record of early Mars displays a variety of features that indicate fundamental differences from more recent conditions. These include evidence for: (1) widespread aqueous alteration and phyllosilicate formation, (2) the existence of an active magnetic dynamo, (3) the erosion of extensive valley networks, some thousands of kilometers long, (4) a much more significant role of impact cratering, forming structures up to the scale of large basins, and (5) the construction of much of the Tharsis volcanic province. Mars also is likely to have had a much thicker atmosphere during this early period. We discuss and review the temporal relationships among these processes and conditions. Key observations from this analysis suggest the following: (1) the last large impact basins, Argyre, Isidis, and Hellas, all pre-date the end of valley network formation, potentially by several hundred million years, (2) the magnetic dynamo is likely to be ancient (pre-Hellas), since the center of Hellas and other young basins lack magnetic remanence, and (3) the period of phyllosilicate formation is not readily connected to the period of valley network formation. Concepts for the possible formation and evolution of life on Mars should address this time sequence of conditions.

1. Introduction

Spacecraft data indicate that the early environment of Mars differs from recent conditions in a multitude of important ways (see, e.g., Solomon et al., 2005; Carr and Head, 2010). Before the mid-Hesperian, Mars appears to have had higher impact flux (Hartmann and Neukum, 2001), a wetter surface (e.g., Carr, 1996; Craddock and Howard, 2002), more volcanic resurfacing (Tanaka et al., 1987), neutral-pH aqueous alteration (Bibring et al., 2006; Murchie et al., 2009), an intense magnetic dynamo (Acuña et al., 1999), and possibly a denser atmosphere (e.g., Jakosky and Philllips, 2001). More speculatively, Mars may have had an ocean on its Noachian surface (Baker et al., 1991; Clifford and Parker, 2001; Di Achille and Hynek, 2010); direct evidence strongly favors the existence of many large lakes (see, e.g., Irwin et al., 2002; Fassett and Head, 2008a). Each of these factors, with the possible exception of a higher impact flux, is broadly consistent with a more habitable Mars in the Noachian to Early Hesperian than at present. The potential habitability of the ancient planet has helped motivate an exploration strategy predicated on examining geological materials from this early period (e.g., Grotzinger, 2009).

However, given the fact that conditions on early Mars appear distinct from those observed today, it is common to assume that there is a discrete geological period perhaps of some length when *all* of these conditions existed simultaneously (active magnetic field, valley formation, erosion and transport, aqueous alteration, etc.). Although such a scenario is possible, a variety of observations constraining the timing of these processes suggests that it may not be the most probable scenario. In this paper we review the constraints on the timing of various conditions based on stratigraphy, crater counting, inferences from the martian meteorite ALH84001, and a variety of orbital observations.

1.1. Crater statistics and the age of surfaces and materials

Given our current lack of samples acquired from known locations on Mars, the primary technique for deriving ages of surfaces or geomorphic features is to measure their superposed crater size-frequency distribution (e.g., Hartmann, 1966; Soderblom et al., 1974; Neukum and Wise, 1976; McGill, 1977; Tanaka, 1986; Barlow, 1988, 1990; Strom et al., 1992; Hartmann and Neukum, 2001; Neukum et al., 2010). Since craters are presumed to accumulate in a spatially random process, at least insofar as the crater population is dominated by primary impactors, areas with higher spatial densities of craters are interpreted to be older. If a reasonable model for the rate at which craters are accumulating can be obtained (e.g., Hartmann and Neukum, 2001), absolute ages can be estimated. These are model dependent, and are therefore less definitive than relative age determinations.

A complicating factor in using craters to derive relative or absolute ages is that the number of craters observed in a given region is not independent of its geological history. Gradation, erosion, and exhumation can remove craters from the surface population or

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