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The digital global geologic map of Mars: Chronostratigraphic ages, topographic and crater morphologic characteristics, and updated resurfacing history☆

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ABSTRACT

A new global geologic map of Mars has been completed in a digital, geographic information system (GIS) format using geospatially controlled altimetry and image data sets. The map reconstructs the geologic history of Mars, which includes many new findings collated in the quarter century since the previous, Viking-based global maps were published, as well as other discoveries that were made during the course of the mapping using new data sets. The technical approach enabled consistent and regulated mapping that is appropriate not only for the map's 1:20,000,000 scale but also for its widespread use by diverse audiences. Each geologic unit outcrop includes basic attributes regarding identity, location, area, crater densities, and chronostratigraphic age. In turn, units are grouped by geographic and lithologic types, which provide synoptic global views of material ages and resurfacing character for the Noachian, Hesperian, and Amazonian periods. As a consequence of more precise and better quality topographic and morphologic data and more complete crater-density dating, our statistical comparisons identify significant refinements for how Martian geologic terrains are characterized. Unit groups show trends in mean elevation and slope that relate to geographic occurrence and geologic origin. In comparison with the previous global geologic map series based on Viking data, the new mapping consists of half the number of units due to simpler, more conservative and globally based approaches to discriminating units. In particular, Noachian highland surfaces overall have high percentages of their areas now dated as an epoch older than in the Viking mapping. Minimally eroded (i.e., pristine) impact craters $\geq$3 km in diameter occur in greater proportion on Hesperian surfaces. This observation contrasts with a deficit of similarly sized craters on heavily cratered and otherwise degraded Noachian terrain as well as on young Amazonian surfaces. We interpret these as reflecting the relatively stronger, lava-rich, yet less-impacted materials making up much of the younger units. Reconstructions of resurfacing of Mars by its eight geologic epochs using the Hartmann and Neukum chronology models indicate high rates of highland resurfacing during the Noachian (peaking at 0.3 km^2/yr during the Middle Noachian), modest rates of volcanism and transition zone and lowland resurfacing during the Hesperian (~0.1 km^2/yr), and low rates of mainly volcanic and polar resurfacing (~0.01 km^2/yr) for most of the Amazonian. Apparent resurfacing increased in the Late Amazonian (~0.03 km^2/yr), perhaps due to better preservation of this latest record.

1. Introduction

Geologic maps provide, in a historical context, fundamental syntheses of knowledge of the materials, landforms, and processes that characterize planetary surfaces. Global maps provide a unique, all-encompassing assessment of the spatial and temporal sequences of geologic events that dominated the surface of a particular planet. For Mars, the first global geologic map was produced on a photomosaic of 1–2 km/pixel Mariner 9 images at a 1:25,000,000 scale (Scott and Carr, 1978). Next, Viking Orbiter data having resolutions of 100 to 300 m/pixel were used to generate a series of three 1:15,000,000-scale maps (Scott and Tanaka, 1986; Greeley and Guest, 1987, Tanaka and Scott, 1987). From these maps, an eight-epoch chronostratigraphy was developed for Mars, which resulted in page-sized time-stratigraphic maps of the surface (Tanaka, 1986). The maps were then assembled and

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synthesized digitally, and estimates of the resurfacing rates were determined for each mean epoch age by geologic process for both Hartmann- and Neukum-based chronologies (Hartmann and Neukum, 2001; Ivanov, 2001; Neukum et al., 2001; Hartmann, 2005; Tanaka et al., 1988). These rates were later revised according to new age assignments to the epochs (Hartmann and Neukum, 2001). These studies indicated that the highest resurfacing rates on Mars occurred during the Middle Noachian, with an apparent resurgence of geologic resurfacing during the Early Hesperian, perhaps driven by widespread volcanism.

The new generation of Mars orbital topographic and imaging data constitutes a significant improvement in the quality and resolution of morphologic and imaging information that justified a major new global mapping effort. In particular, Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) data provide an unprecedented set of accurate topographic and morphologic data in the form of a digital elevation model at $1/128^\circ$ resolution (463 m/pixel at the equator) (Smith et al., 2001). These data have supported significant new advances in geologic mapping at a global, 1:15,000,000 scale for the Martian northern plains (Tanaka et al., 2005). In addition, Mars Odyssey (ODY) Thermal Emission Imaging System (THEMIS) near-infrared (IR) day and night-time images (100 m/pixel) and Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) images (5–6 m/pixel) have complemented the MOLA data in support of the new global geologic mapping. The THEMIS day IR images are generally more effective at revealing morphologic details than visual-range Viking images.

Advances in mapping approaches applied to Mars address how units should be identified, mapped, named, grouped, and colored (Skinner and Fortezzo (2013); Tanaka et al., 2005). Contact types and structures have been revisited as well. Blind photogeologic mapping tests of well-understood terrestrial sites with data sets that mimic altimetry and image data acquired by Mars spacecraft indicate how to optimally split and lump potential map units and how to determine the accuracy of topographic- and morphologic-based relative-age inferences (Tanaka et al., 2009; Skinner and Fortezzo, 2012). These analyses have optimized the methodologies that have been applied to geologic mapping of Mars at global scale. Thus, the mapping approach used in the Viking-based map series differs from that of the new map in a few important ways. First, many of the Viking-based units included formation names that applied to local and regional features, such as large volcanoes, that have been grouped in the new map. Second, some of the Viking-based units are geomorphic variations of what is otherwise the same material unit. Third, lava sequences in the vast Tharsis volcanic complex were divided by relative age, but the new mapping indicates that the surface flows are much more spatially and temporally mixed than previously appreciated, even though the same general trends in age are confirmed. This resulted again in some reduction in units. Finally, the new mapping approach emphasizes simplicity, and so there is a tendency to combine units if there is not a compelling reason to split them. Overall, the number of Viking-based units mapped is 88 and other areal, geomorphic features (e.g., small volcanoes, channel bars, mountains) number seven. In contrast, the new map has 44 units and no areal features.

Planetary geologic maps were originally drafted by hand, commonly on image mosaics or air-brushed shaded relief bases that were also produced manually. With the advent of digital mapping technologies, maps and map bases are generated and manipulated using software that has increased in capability and sophistication over time. In addition, scanning and digital drafting have enabled conversion of manually drafted geologic maps into digital formats, including geographic information system (GIS) shapefiles and geodatabases—currently the most advanced digital mapping approach.

Compiling and publishing geologic maps in a digital format has many advantages. Digital maps permit accurate spatial statistical measurement and calculation of map properties, such as the areas of map units and outcrops and the lengths and orientations of linear features and densities of linear and point features. Also, comparisons can be made with other, spatially co-registered datasets and thematic maps that relate to composition, topography, crater density, and other surface physical characteristics, as well as with previous mapping results. This has been the case in the application of the previous geologic map of Mars, which was published on three sheets at a 1:15,000,000 scale in Mercator and Polar Stereographic projections (Scott and Tanaka, 1986; Greeley and Guest, 1987, Tanaka and Scott, 1987). Later, the map was digitized and used to reconstruct the resurfacing history of Mars (Tanaka et al., 1988), and eventually renovated into a GIS format that registers more accurately with the current geodetic and topographic definition of Mars (Skinner et al., 2006).

In this paper, we summarize the methods and results of geospatial analyses that we conducted on the new global geologic map of Mars (Tanaka et al., in review). Derived thematic mapping products of Mars include (1) chronostratigraphy and (2) resurfacing for each major chronologic period (Noachian, Hesperian, and Amazonian) by unit type. We also combine the mapping and chronostratigraphic determinations in order to reconstruct the quantitative resurfacing history by epoch and model-dependent absolute ages. We present comparisons of mapping with global digital elevation and slope models and with impact crater morphologies determined for all craters >3 km in diameter. Results provide global statistics that assist with both characterizing map units and unit groups as well as with providing lithologic and geographic context to evaluate other geospatially registered information.

2. Digital map product

The new global geologic map of Mars at a 1:20,000,000 scale (Tanaka et al., in review) was drafted and produced in a geographic information system (GIS) using the Environmental Systems Research Institute, Inc. (v. 10.0, ®1980–2012, Redlands, CA) ArcGIS software package. The geologic map is registered to the Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA) global digital elevation model (DEM) at 463 m/pixel horizontal spacing at the equator constructed from ~600 million laser ranging measurements having accuracies of ~100 m in a horizontal position and ~1 m in radius (Neumann et al., 2001; Smith et al., 2001) and geodetically fixed using the currently accepted model of Mars (Seidelmann et al., 2002). Some interpolation occurs in the DEM in equatorial latitudes, where east-west gaps between altimetry shots reach a few kilometers or more in places, and in the polar regions above $\pm 87^\circ$ latitudes, over which the spacecraft did not directly track. The mapping also relied heavily on morphologic and brightness observations from global mosaics of Mars Odyssey (ODY) mission's Thermal Emission Imaging System (THEMIS) daytime and nighttime infrared images at 100 m/pixel spatial resolution (Christensen et al., 2004; Edwards et al., 2011). In a few cases, critical landforms required for identification of units and contacts were too small to resolve on THEMIS images; in these cases, the mapping relied on Mars Reconnaissance Orbiter Context Camera (CTX) images (5–6 m/pixel) to locate contacts, which could in turn be located on THEMIS data.

Drafted unit contacts and line features consist of polylines—segmented lines of connected sequences of vertices (points). The mapping was mostly performed at the 1:5,000,000 scale (25% of the map's publication scale; Tanaka et al. (in review)) using a vertex spacing of 5 km, which sufficiently propagates the fidelity