THE 'NEW' GEOLOGY OF MARS: TOP TEN RESULTS OF POST-VIKING GLOBAL MAPPING AND CRATER-DATING. K. L. Tanaka[1], J. A. Skinner, Jr.[1], C. M. Fortezzo[1], T. M. Hare[1], R. P. Irwin, III[2], T. Platz[3], G. Michael[3], J. M. Dohm[4], E. J. Kolb[5], and S. J. Robbins[6]. [1]Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff AZ 86001, USA, ktanaka@usgs.gov; [2]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington DC, USA; [3]Planetary Sciences & Remote Sensing, Freie Universität Berlin, Berlin, Germany; [4]Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan; [5]Google Inc., Mountain View CA, USA; [6]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO, USA.

Introduction: The orbital imaging campaigns of Mars by Mariner 9 and the Viking Orbiter missions enabled publication of the first global geologic maps of a planetary body outside of the Earth-Moon system first in 1978 [1] and again in 1986-87 [2]. These maps documented Mars' major rock types, surface features, and geologic processes in a time-stratigraphic context. The Mariner 9 map established the Noachian, Hesperian and Amazonian Periods based on mapping relations [1], which were later subdivided into eight epochs and assigned crater-density boundaries on the basis of Viking data [3] (the crater-density boundaries were recently refined by [4]).

A decade later, remote-sensing of Mars increased dramatically through collection of diverse, high-quality data sets from a new generation of sophisticated scientific instruments flown on the Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter polar-orbiting spacecrafts. Further enhancements in analysis have been derived from advanced data-processing techniques and mapping capabilities. As a result, a meaningful, third-generation remapping of the global-scale geology of Mars has been made possible.

At the time of this writing, the newest global geologic map of Mars has been completed [5], as well as related journal articles that document crater-counting results, Noachian highland evolution, resurfacing rates, and other map-based findings [6-8]. Here, we summarize the mapping approach and methodology and the 'Top Ten' key new findings and understandings collectively achieved by these efforts and publications.

Mapping Approach and Methodology: Our mapping team gave considerable attention to how units were delineated, grouped, drafted, and dated with crater statistics and superposition relations. Our goal was a true global map, having map units defined by their relative age ranges, geomorphology, and primary geographic and/or geologic characteristics. Minimum outcrop- and feature-size requirements were also defined that were appropriate to the 1:20,000,000 scale, and drafting was generally performed at 1:5,000,000 scale for precision. Contacts appear either as "certain" (solid lines) or "approximate" (dashed lines) depending on how precisely the contact could be located. All map drafting is digitally recorded in geographic information system (GIS) format. The two primary data sets serving as mapping bases were the Mars Orbiter Laser Altimetry (MOLA) digital elevation model (at ~460 m/pixel or better) and the Thermal Emission Imaging System (THEMIS) daytime mosaic (100 m/pixel).

Crater-count type localities were identified for as many units as possible to provide precise, representative crater size–frequency distributions (CSFDs) to help with defining unit ages [5, 7]. Counts were performed on High-Resolution Stereo Camera (HRSC; ~20 m/pixel) and Context Camera (CTX; ~6 m/pixel) images; in addition, each of the 48 crater counts met a statistical spatial randomness test [7]. In some cases, however, units either had already been crater counted sufficiently in previous work or were problematic for crater dating. The age ranges for each unit were then derived from the combination of map-unit superposition relations and crater dating results.

This mapping approach resulted in 44 units (in contrast, the Viking global map-series [2] at 1:15,000,000 scale resulted in 90 units). Each unit is assigned to one of the following groups according to their dominant geographic occurrence or lithology: highland, lowland, transitional, basin, polar, apron, volcanic, and impact. Within unit groups, subdivisions are made based on relative age and primary morphologic features. Unit descriptions include additional characteristics, including documentation of mineralogies from spectral data [e.g., 9] and ice composition where determined by radar sounding [e.g., 10] as well as genetic interpretations derived from mapping observations and other studies in the literature.

Our mapping also benefited from inclusion of the global digital crater database of more than 380,000 craters $\geq$ 1 km in diameter [11]. This database enabled us to automatically determine crater densities; or we could select pre-measured, superposed craters for dating the surface pertaining to the unit of concern (and thus excluding buried craters that predate the unit). Based on these crater-density results, ages of individual outcrops could be determined to verify (and modify where necessary) their unit assignment.

The 'Top Ten': Because of the improved topographic and imaging data used for mapping, the carefully considered mapping approach applied, the much more thorough crater dating of units and outcrops, and the consideration of hundreds of relevant and complementary topical studies in the scientific literature, the resulting map portrays a more accurate, precise, detailed, and understood representation of the geology of Mars than presented in previous global maps. There are innumerable changes to the mapping and characterization of the Martian surface. Our 'Top Ten' new results list includes:

1. Mars is appreciably older overall, with much more Early Noachian and much less Hesperian surfaces than previously understood (Viking-based values [12] in parentheses): The Early Noachian makes up 12% (4%) of the surface, Middle Noachian 24% (24), Late Noachian 9% (12), Early Hesperian 10% (16), Late Hesperian 21% (19), Early Amazonian 12% (11), Middle Amazonian 6% (8), and Late Amazonian 6% (7). Although the epoch system remains the same, the referent units that it is based on have been updated with new units that are generally more accurately mapped and their CSFDs more fully determined.

2. Highland units are the most extensive unit group, making up 44% of the surface, followed by volcanic (22%), lowland (13%), transition (10%), impact (5%), polar (3%), basin (2%), and apron (1%) units.

3. Resurfacing rates based on the new mapping and latest cratering chronology are determined per epoch and unit group [8]. The new results show differences in detail but *overall* trends similar to the previous results, including the bias toward higher rates for younger surfaces due to partial burial of older surfaces [12].

4. Early, Middle, and Late Noachian highland units have statistically distinct ages, and the units occur at progressively lower mean elevations with successively younger age. Crater morphology statistics indicate that Noachian resurfacing was spatially non-uniform, long-lived, and gravity driven, which is consistent with volcanism and arid-zone fluvial and aeolian erosion [6].

5. All well-preserved impact basins >150 km in diameter identified by [13] have been dated and show a dramatically reduced rate of formation over time: >65 for Early Noachian, >15 for Middle Noachian, ~3 for Late Noachian, ~4 for Hesperian, and 2 for Early Amazonian. Of these, Hellas is Early Noachian whereas Isidis and Argyre are assigned to the Middle Noachian.

6. We mapped a variety of volcanic-flow units largely based on their relative age ranges determined by crater counts and superposition relations. However, for much of the central parts of the Tharsis and Elyisum rises, there is much overlap of Hesperian to Amazonian volcanic flows that cannot be separated by geomorphic mapping at global scale. Although there is a general increase in flow age radially outward from the summit regions of the rises, we could not map these changes consistently and thus merged the flows into a Amazonian and Hesperian volcanic unit (a departure from how these regions were mapped based on Viking data [2]). In two instances, we mapped internal contacts within outcrops of the Late Hesperian and Late Amazonian volcanic units where clear overlap relationships between sets of flows permitted this.

7. New mapping improves presentation of geologic relationships among tectonic landforms, impact craters, fluvial valleys, and other erosional landforms >100 km long. Where the features are dense and overlapping, selective mapping ensured representation of key orientations and patterns without over cluttering.

8. The layered, deeply eroded deposits of what are commonly known as the Medusae Fossae Formation were previously mapped as three Amazonian units [2]. In our map, we divide the materials into two units ranging from Hesperian to Amazonian that respectively pre- and post-date a depositional hiatus during the Hesperian. This revised crater dating is consistent with results by other workers [e.g., 14].

9. A subtle Middle Amazonian lowland unit is included in the map that has been crater dated extensively [15]. The unit likely resulted from a climate excursion and temporally and spatially correlates with layered material making up crater pedestals in the northern plains [16].

10. Volcanic fields consisting of multiple small shields, vents, and flows were mapped for the first time at global scale in the Tharsis and Elysium regions; these are either Late Amazonian or Late Hesperian in age. Also, highly degraded edifices of uncertain but suspected volcanic origin were mapped as the Noachian highland edifice unit, whereas more convincing examples were designated as volcanic edifice units.

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