MARS GEOLOGIC MAPPING: THE NEXT GENERATION. K. L. Tanaka[1,*], James M. Dohm[2], Trent M. Hare[1], R. P. Irwin, III[3], E. J. Kolb[4], and J. A. Skinner, Jr.[1], [1]U.S. Geological Survey, Flagstaff, AZ ([*]ktanaka @usgs.gov), [2]U. Arizona, Tucson, AZ, [3]Smithsonian Inst., Washington, DC, [4]Arizona State U., Tempe, AZ

Value of geologic mapping efforts and products. Geologic maps are invaluable research products that form a comprehensive basis and context for reconstructing local- to regional-scale geologic histories. On Mars and other extraterrestrial planets, a compilation of both local- and regional-scale geologic maps afford various perspectives for interpreting bedrock structures, tectonic evolution, surface impact history, and atmospheric-driven erosional resurfacing, to name a few. These maps are constructed through the careful analysis and synthesis of available image, topographic, and other data sets. Geologic maps provide collective (and sometimes contrasting) views of the spatial and temporal relations among mapped units and features, constraining interpretation of genetic relationships, formational and modificational processes, and history. Such maps should be used to garner invaluable context to a broad range of topical studies and contextual information that can assist with current and future mission planning and operations, including landing-site selection.

Three generations of Mars maps. We are in the third major period of Mars geologic mapping, as driven by data and scientific objectives. The first phase occurred in the 1970s and was based on Mariner 9 images, the first global data set for Mars. The major products of this episode consisted of 30 quadrangles at 1:5M scale, from which a global map at 1:25M scale was synthesized [1]. The next two-plus decades saw dozens of maps based on Viking image data, ranging from 1:500K local-scale maps to 1:15M hemispheric-scale maps [2]. These first two generations of mapping resulted in definition of a stratigraphy and corresponding chronology including definition of the Noachian, Hesperian and Amazonian Periods [1] and their subdivision into epochs [3], based on both superposition relations of geologic units and impact crater densities.

We are now in the third generation of Mars geologic mapping, which utilizes higher quality and resolution data sets from multiple spacecraft, new digital tools, and improved mapping techniques. Current investigations range from 1:200K detailed maps of Olympus Mons caldera and Tooting crater by P.J. Mouginis-Mark (U. Hawaii) to our newly approved 1:20M global map. (For a complete list of recent Mars maps, see: http://astrogeology.usgs.gov/Projects/-PlanetaryMapping/MapStatus/MarsStatus/Mars_-Status.html.)

Third generation mapping. The present phase of the geologic mapping of Mars is in its infancy and is thus constantly evolving. New and improved data, tools, and approaches combine to ensure that the geologic maps now being assembled will be much more accurate and useful to scientists and mission planners than their predecessors.

New data sets and geodesy. The most important reasons that current geologic mapping of Mars is superior to efforts previously based on Mariner 9 and Viking data are the new mapping and characterization data sets obtained by Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Express (MEX), and Mars Reconnaissance Orbiter (MRO). These have better quality and spatial control, a wider range and increased number of spectral bands, and higher spatial resolution than was previously available. Data types that can be used to make geomorphic observations, the backbone of photogeologic mapping, include altimetry (transformed into raster digital elevation models) and visual and thermal-infrared range images (Table 1).

Table 1. Mars geologic mapping data sets. *MOLA = MGS Mars Orbiter Laser Altimeter; THEMIS = ODY Thermal Emission Imaging System; HRSC = MEX High Resolution Stereo Color camera; CTX = MRO Context Camera; IR = infrared, VIS = visual range.*

Data	Type	Resolution (m/pixel)	Current coverage
MOLA	Altimetry	460 (115 at poles)	global
THEMIS IR	Infrared images	100	global
HRSC	Color, stereo images	10 to 30	extensive
THEMIS VIS	Visual range images	18 to 40	patchy
CTX	Visual range images	6	little

The MOLA data also have been used to fine-tune the shape of Mars [4] and provide topographic reference points to which other data sets need to be spatially registered. Higher resolution images such as from MOC narrow angle, HiRISE, and super-resolution HRSC have footprints too small for most formal mapping endeavors, but they are invaluable for solving local problems that influence the mapping. HRSC coverage permits mapping of many regions of interest at higher resolution than THEMIS IR. THEMIS VIS images are patchy, but some areas of the planet are sufficiently covered (the poles and other specific targets of interest) to support local mapping. CTX coverage may also eventually provide high-quality coverage for local, detailed mapping.

Other data sets used to determine mineralogy (e.g., MGS Thermal Emission Spectrometer (TES), MEX OMEGA, and MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)), chemical composition (ODY Gamma Ray Spectrometer), and various physical properties can help characterize the materials making up map units. However, in many cases the instruments are sensitive to surficial properties to a depth of less than one meter and averaged over a broad area. Thus the information does not provide a proper "base" from which to map, but it does provide previously unrecognized mineralogical information and other characteristics of the unit. These may help yield information about primary rock unit formation, material provenance (in the case of sedimentary units), and how the materials were modified. Radar-sounding data from MEX Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) and MRO Shallow Subsurface Radar (SHARAD) can provide information on the presence and character of subsurface water and ice, as well as tectonic and sedimentary structures that can assist in interpretation of geologic mapping.

Digital tools. Earlier geologic maps were hand-drafted and colored, resulting in products that were difficult to edit and redraft. Map bases were poorly controlled compared to what is achievable today. For example, the 1:15M base originally used for the Viking-based global map [2] was a manual, air-brush product (this map linework has been redrawn and digitally to conform to the current MOLA-defined geodesy and topography [5]). Now, map drafts can be prepared digitally using Geographic Information Systems (GIS) software tools. This approach eases the editing process and enables sharing of drafted work with co-authors and reviewers. It also permits online publication of updated versions, as they become available. Moreover, and perhaps most importantly, GIS users can import digital, georeferenced geologic maps and execute a variety of spatial analyses.

Mapping approaches. A long-term challenge in planetary geologic mapping has involved how to name units based on their geomorphic signatures. In many cases, past Martian geologic units were constructed using a specific geomorphic characteristic(s) that was not always consistently distributed across the entire planetary surface. Moreover, some unit descriptors were of landforms that were secondary in origin; that is, they formed after unit emplacement due, for example, to tectonic deformation (e.g., *ridged* plains), mass-wasting and/or erosion (e.g., *knobby* plains unit), or periglacial processes (e.g., *grooved* material). Such unit names are inherently non-stratigraphic, and often lead to confusing and/or inaccurate reconstructions of geologic history [6]. Because of such problems, it became clear that adjustments in mapping and unit-naming approaches were needed to more accurately discern and portray the stratigraphic contact relations between map units. On this basis, allostratigraphic, or unconformity-bounded units, were advocated [7], which define geologic units based on contact relations that indicate significant hiatus between units. Other types of units, including some previously mapped, can be delineated through other kinds of stratigraphic relations that provide clearly-defined contacts. Such units do not require geomorphic descriptors and can be named more objectively by avoiding a genetic or geomorphic connotation and relying more strictly on geographic names (e.g., Isidis Planitia unit), similar to terrestrial mapping practices. Renovated mapping schemes and styles such as these were employed in the new-generation geologic map of the northern plains of Mars at 1:15M scale (Fig. 1) [8].

Field validation studies. One of the common challengers to photogeologic mapping is whether to lump or split map units. When is there sufficient information to justify splitting into discrete units, as has been previously done for lava flows (and other materials) on Mars [e.g., 2]? Or, what is a justifiable and valid rule of thumb when "similar appearing" occurrences of materials neither are adjacent to one another nor are large enough to yield meaningful crater densities? There are studies underway to address such issues that involve photogeologic-style mapping of terrestrial sites using digital data similar to that available for Mars [9]. These exercises are proving useful, because they permit comparison of photogeologic mapping results with field-mapping assessments. These efforts help illustrate how to improve accuracy in mapping and where difficult-to-appreciate pitfalls can be avoided. As the results of ongoing studies are reported, new guidelines and refined approaches will be employed in our newly-funded third-generation global map based on the lessons learned.

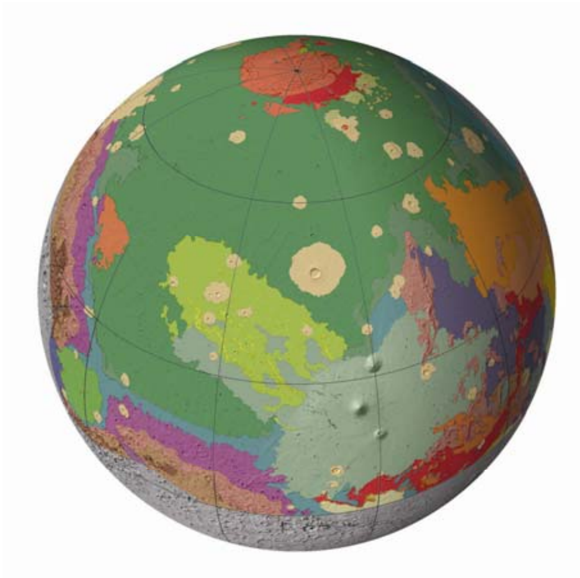

Fig. 1. Part of the geologic map of the northern plains of Mars [8] projected on a sphere showing Utopia Planitia, the Elysium rise, and Planum Boreum (MOLA shaded relief base).

New global geologic map. We recently received NASA funding to remap the global geology of Mars at 1:20M scale (printed), which will employ the lower resolution mapping data sets in Table 1 and the digital tools and approaches mentioned in the previous section. Our work plan runs for five years (2007 to 2011; the Viking-based global map at 1:15M scale and more recent northern plains map at 1:15M scale each took ~six years to complete). Our team includes additional colleagues who will contribute mapping of particular features and regions, perform detailed crater counts, and provide additional analyses of the mapping results. Along the way, we will present our progress, including preliminary results and updated thinking about geologic and stratigraphic schemes for Mars. We will encourage input from the planetary geology community during the course of the project as the results of concurrent studies by others will help us to improve our global geologic map in various ways.

Issues that can be addressed. Our newly-funded global mapping project will achieve a better understanding of the global geology of Mars. In particular, we will focus on the following science objectives.

1. Update global stratigraphy. Each previous global map of Mars has resulted in constructions and formal definitions of global stratigraphic and chronologic schemes, first with the establishment of the Noachian, Hesperian, and Amazonian Periods from Mariner 9-based mapping [1], and later with the subdivision of the periods into Early, Middle, and Late epoch divisions using Viking images [2-3]. A "pre-Noachian epoch" was introduced in the northern plains map [8], based on the recognition of quasi-circular depressions indicative of primordial, buried crustal material underlying the oldest determined exposed Noachian surface materials [10]. Another major stratigraphic revision was the re-assignment of the beginning of the Amazonian Period to the surface age of the Vastitas units of [8] (those units are roughly equivalent to the Vastitas Borealis Formation of [2]). These units are much more geologically and spatially significant and broadly coeval than the lava flows of Amazonis Planitia previously used as the basal Amazonian stratigraphic marker, which are now perceived to have a complex stratigraphy [8]. Global mapping will provide us with the proper perspective to consider whether any other significant revisions to the unit-based stratigraphic divisions ought to be made, such as to represent younger deposits related to climate cycling [8, 11-12], as well as re-evaluation of each Martian epoch.

Furthermore, discrepancies exist in crater size-frequency distributions at the most critical diameter range, between ~1 and 20 km, where the distributions are most at odds [13]. Discrepancies also exist at larger diameters [cf. 14-15]. Our work will provide an extensive database of crater size-frequency data as a function of geologic unit in these critical diameter ranges. The new mapping and crater statistics, when applied judiciously (with proper consideration to resurfacing) will result in an improved scheme of Martian epochs defined by crater densities. In turn, ages and rates of geologic activity can be estimated [e.g., 13], which can be useful for scientific and mission-related applications.

2. Update global tectonic history. Global structural mapping will permit refinement of the tectonic history for Mars, as follows:

(a) Contractional history. Viking-based mapping of wrinkle ridges recognized few ridges in the northern plains and indicated stress sources primarily due to Late Noachian and Early Hesperian global contraction and local compression caused by outflow channel erosion and Tharsis tectonism [16]. MOLA shaded-relief and detrended maps and THEMIS day IR images permit identification and mapping of wrinkle ridges previously unrecognized in Viking images [8]. Furthermore, some wrinkle ridges located in the northern plains may have been active more recently than previously- interpreted, perhaps during the Late Hesperian and Early Amazonian [8]. Remapping and relative-age

dating of wrinkle ridges will better constrain lithospheric stress history, particularly in the highlands.

(b) Extensional history. We do not expect significant alteration to the line mapping of extensional structures such as graben and rifts because much of the original printed maps have been digitally renovated, including improved spatial registration [5]. This renovation improved the positioning of previously mapped tectonic structures, which enabled their accurate registration to more recent global data sets (e.g., MOLA DEM and MDIM 2.1) [5]. We do, however, anticipate some refinement in the constraints to dating of these features as they relate to newly-defined geologic units and their boundaries. We can also more adeptly assess relative-age information for globally-mapped tectonic features through application of digital tools, improved mapping, and more detailed crater counting of the map units that constrain their ages. Impact craters and their preservation states can be more precisely delineated and characterized using third-generation images such as by THEMIS IR images than with panchromatic, visible-range Viking images.

3. Analysis of fluvial valleys, paleolakes, oceans, and surficial mantles. Our global mapping will provide the broadest context to search for geologic associations that various climatic/hydrologic scenarios predict. We can document the relative timing and spatial relations of major fluvial, mass wasting, and potential glacial erosion vs. age of emplacement of sedimentary and other possibly related units. For example, a significant gap in time between valley network activity and plains emplacement would suggest non-fluvial materials, whereas contemporary deposits would be consistent with a fluvial origin or perhaps a combined fluvial and volcanic suite where magma/volatile interactions have occurred.

The relative-age relationships between fluvial erosion and extensive mantling (sedimentary or volcanic) events will help to characterize the activity during waning stages of activity, perhaps when the supply of water was episodic. In areas where extensive eolian deflation has not occurred, mantle deposits can be dated relative to fluvial activity by simple cross-cutting and burial relationships. In addition, catastrophic floods sourced from chaos within highland material may have ponded in the northern plains as transient oceans and/or lakes, perhaps causing the punctuated development of short-lived (tens of thousands of years?) regional to global hydrologic cycles and climatic perturbations. The latter may have caused environmental conditions (and, thus, geologic conditions) at the surface to deviate, perhaps significantly, to an unusually warm and wet Mars [e.g., 17-19]. Despite such assertions, geologic evidence for a paleo-ocean remains inconclusive [e.g., 19], perhaps because the large amount of time since their putative existence has allowed for thorough erosional masking. Oceans may also have formed by elevation-controlled surface runoff [20] or ground-water discharge [21-22], hypotheses that can be tested with a global map and the MOLA data set. Alternatively, topographically-controlled groundwater basins may have inhibited the delivery of highland recharged groundwater to a putative northern ocean. We can also assess the timing and distribution of features potentially related to precipitation and ground-water recharging hypotheses that involve sapping [e.g., 22] and tapping of Tharsis and east Hellas aquifers that led to catastrophic discharges evident in the carving of outflow channels [23-24].

4. Other volatile-related processes. These processes include deposition and exhumation of ice and dust mantles [11], volatile-exchange and weathering in near-surface materials (including formation of phyllosilicates and hydrous sulfates [25-26]), and cryoturbation and soft-sediment deformation [27]. Global examination of such processes will help us understand the volatile history within the near surface and its relation to geologic and climate history.

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