MARS: UPDATING GEOLOGIC MAPPING APPROACHES AND THE FORMAL STRATIGRAPHIC SCHEME. K. L. Tanaka and J. A. Skinner, Jr., U.S Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001; ktanaka@usgs.gov.

Introduction: At the Fourth Mars Conference in 1989, Tanaka reviewed the stratigraphy and geologic history of Mars that had emerged based on systematic geologic mapping of the planet's surface using Viking data [1]. This review looked at the stratigraphic column for Mars and assessed the global geologic history in terms of impact, fluvial, periglacial, aeolian, volcanic, and tectonic processes. Many significant new studies using Mars Global Surveyor (MGS) and now Mars Odyssey (MO) data are showing some important new insights and discoveries that are altering and deepening previous understandings. If we were to illustrate the current state of the science, we might compare it to a loose-leaf notebook in which pages are rapidly being added, removed, and rewritten, with plenty of room remaining. Much of the flux is due to new data, of course, but also much can be attributed to the re-examination of basic assumptions and approaches and our ability to employ ever more powerful computer techniques. Here, we will attempt to review, based on our experience, the areas where the most change seems to be occurring, what prospects we face in the immediate future, and where caution needs to be exercised.

Geologic Mapping Approaches: The fundamental technique for reconstructing the history of planetary surfaces is geologic mapping. Maps portray the distribution of rock units and surface features as they developed through time, based on morphologic relative-age indicators including superposition and cross-cutting relations as well as crater-density determinations where possible, as on Mars.

Previous Methods and Their Shortcomings. Generally, map units for Mars have been based on morphology, albedo, relative ages, and topography using Mariner 9 and Viking images. These data have proved to be valuable but challenging to map with, because of inconsistencies in or problems with resolution, atmospheric opacity, solar illumination, and image locating. MGS MOLA data have been extremely valuable in providing improved topographic and morphologic views over much of the planet's surface. However, cross-track spacing is locally quite large in the equatorial region and above 87° latitudes, where off-nadir pointing was required. New, largely nadir visible and thermal infrared images of the surface by MGS MOC and MO THEMIS provide higher resolution and different wavelength views of the surface. MOC NA images reveal close-up views of morphology and albedo features at meters to tens of meters scales such as rock layers and craters [2]. Depending on scale, these new data sets will likely justify revised mapping of Mars.

While the prospects for new results detailing the geologic history of Mars are bright based on new data alone, improved mapping methods will also be significant. Since the days of systematic geologic mapping using Mariner 9 data, Mars geologic map units have been characterized and named on the basis of morphologic and albedo features that we now (as well as previously) realize represent secondary features related to surface modification and tectonic deformation (rather than to the primary origin of the unit). Examples of secondary descriptors in unit names include "ridged," "lineated," "channel," "dissected," "cratered," "mottled," "etched," "knobby," "smooth," and "rough." Albedo seems to be a consistently mappable characteristic only where the surface is free from dust due to recent atmospheric activity; (e.g., polar residual ice, which varies annually in extent), or where the dust and soil themselves are being mapped. However, much of the planet is covered by a shifting mantle of dust as indicated by high albedo and low thermal inertia data.

Some units have composite signatures of significance, but the unit name may focus on only one item. Thus, "knobby material" usually signifies knobs of one material surrounded by plains-forming material of another material type and age. Finally, unit descriptor terms usually have relative and thus imprecise meaning; as an example, a "smooth" surface at small scale may be characterized as "rough" at larger scales. Thus morphology, albedo, and other surficial data must be used with caution, if at all, in defining map units. In many cases, it may be difficult to determine whether particular signatures are primary or secondary (e.g., the high albedo of a rough surface could be primary or it may represent a coating of much younger, high-albedo aeolian material).

The use of secondary features in unit names and definitions engenders the misconception that the secondary features are either primary or at least about the same age as the material unit being mapped. Even worse, mappers may be inclined to map material unit contacts on the basis of the presence or absence of those features without carefully testing this approach. These issues have been addressed in the case of photogeologic mapping of planetary surfaces marked by tectonic structures [3], which is particularly applicable to Venus and outer planet satellites. The Moon, Mercury and Mars also have surfaces displaying sufficient ranges in crater densities to provide an effective tool in relative-age dating. Mars is an especially complex case, because it also has experienced significant erosion. Thus determining the relative ages of secondary features requires special care. For example, feature terminations (e.g., of grabens or valleys) may represent either the original, full extent of the features or the extent to where obliteration has occurred due to resurfacing by erosion, degradation, or burial by younger material. To discriminate between these possibilities, additional evidence is required such as embayment by younger material. It is insufficient to rely solely on a lower crater density where the features are missing, because erosion or the former presence of mantles may account for a lower crater density and not younger material.

While it may be particularly evident that many morphologic and albedo signatures may be secondary and thus should not be included in map-unit definitions and names, we also see a danger in using terrain descriptors, such as "highlands," "plains," "hilly," "floor," and "basement." Such descriptors force the mapper to pigeonhole outcrops on the basis of terrain, although geologic units may actually occur in multiple terrain settings. Furthermore, terrain descriptors do not make sense in cross section, as in "ridged plains material" that may make up kilometers-thick sequences of flows exposed in the walls of Valles Marineris and Kasei Valles or as in "channel floor material" actually made up of scoured older material. In some cases, but not generally, mappers have called these units "geomorphic units," recognizing they represent younger surfaces rather than younger materials. However, such maps suffer from the added complexity of not being fully geologic maps.

Another shortcoming in much of the previous geologic mapping of Mars has been the nature of contact relations among map units, which was not studied carefully, not documented adequately, and/or not mapped in detail using multiple contact types. Thus the reader is left uninformed about the specific inferences and their associated uncertainties used in defining map units, in mapping contacts, and in determining relative-age relations between units. Many contacts among Noachian materials and younger plains-forming materials in particular have been described as gradational, which could mean gradational in morphology, age, lithology, provenance, emplacement processes, etc., with adjacent units.

Improved Mapping Approaches. We are implementing some significant new approaches in our geologic map of the northern plains of Mars (in progress) in order to overcome the aforementioned shortcomings. These approaches may need further refinement and thus should be regarded as tentative.

First, we are not using morphology, albedo, terrain, or any other physical characteristics in map-unit names. Following terrestrial methods, units are named strictly after associated geographic terms (e.g., *Vastitas Borealis* Formation). They may also be distinguished by geochronologic period (e.g., Noachian), relative stratigraphic position (e.g., upper, lower, 1, 2, 3), and/or lateral facies (interior, exterior, marginal, proximal, distal).

Second, we define map units only by their apparent primary features, and secondary features are discussed only as they relate to unit character. Examples of the latter include inferences such as yardangs indicative of friable materials and steep scarps suggestive of resistant material. In addition to lithologic (rock-stratigraphic units), we recommend also mapping unconformity-bounded units (UBUs) [4] (or allostratigraphic units [5]) that discriminate material units by relative age, wherever a significant hiatus can be demonstrated in the geologic record. Also, these units may consist of multiple lithologies, useful when an intimate mixture of diverse lithologies may prove to be impractical to map but all have a geologic and temporal association. Thus lobate materials of diverse, mixed morphologies in Utopia Planitia may include lava and ash flows, lahars, and mudflows of diverse lithology but all related to the same period of volcanism and erosion of the western flank of the Elysium rise as defined by stratigraphic relations and crater counts. Another example would be two sets of overlapping lava flows in which the older set is faulted by grabens and the younger set buries the grabens. While UBUs have been used in essence in previous mapping to some degree, the lack of their formal recognition as a legitimate unit type has resulted in inconsistency in their application.

Third, we avoid discriminating units having considerable overlap in both character and age. We thus have not separated out both Late and Middle Noachian highland units in our northern plains mapping (as in the cratered and subdued units of the plateau sequence as mapped previously [6]). Most Noachian surfaces show high variability in crater densities and terrain ruggedness, but few display strong morphologic indications of embayment and overlap relations that relate to distinctive epochs. We only have mapped within ~300 km of the highland/dichotomy boundary; and Late Noachian materials appear to occur elsewhere, such as material covering Thaumasia Planum south of Coprates Chasma [7].

Fourth, we attempt to lump or split units based on geologic associations at map scale. This is not a new approach, but implementing it has improved now that MOLA and other new data better define topographic and other associations for provenance of deposits and source regions of volcanic flows.

Fifth, we more carefully define and map contact types according to USGS standards [8], including: certain, approximate, gradational, inferred, and inferred approximate.However, the USGS guidelines seem to be poorly defined, so we have provided our own: *Certain* denotes a precise contact between well-characterized material units, whereas *approximate* contacts are less precisely mapped due to data quality, subtlety of the contact, and/or secondary surface modification. *Gradational* contacts are used around composite units made up of intimate mixtures (at map scale) of older materials and their apparent erosional products, such as knobs of older material surrounded by younger slope material; such units grade with adjacent, continuous outcrops of both the older material and younger plains-forming material at the base of the knobs. *Inferred* contacts are used when the material distinctiveness between the map units is subject to question. An example is the contact between what we are mapping as the interior and marginal members of the Vastitas Borealis Formation. The interior member may be simply a different morphologic expression of the same material and emplacement age as the marginal member, or it may represent material of the marginal member that was later pervasively and intensely reworked. Digital mapping of line work greatly facilitates the drafting and editing of multiple contact types.

The Formal Martian Stratigraphic Scheme: Surprisingly, the scheme initially introduced by Scott and Carr [9] from Mariner 9 based global geologic mapping and later refined using Viking global geologic mapping results and crater-density data [1], has fairly well withstood the test of time and dozens of local and regional studies in the assigning of relative-ages based on crater densities and stratigraphic relations. However, aspects of the scheme are either flawed or need revisiting.

Referents and Time-Stratigraphic Units. The present stratigraphic scheme for Mars is based on the formal time-stratigraphic methodology developed for Earth [5]. Time-stratigraphic (or chronostratigraphic) units define stratigraphic position and are based on rock units that can be used to define a specific period of geologic time; the base of the unit represents the beginning of the period. Time-stratigraphic units form Systems and their subdivisions, Series, and their chronologic equivalents are Periods and Epochs. Thus heavily cratered material in Noachis Terra defines the Noachian System position and the Noachian Period age category, and intercratered plains material defines the Upper Noachian Series, corresponding to the Late Hesperian Epoch [1].

Increasingly, it is apparent that using material referents to define the spans of time-stratigraphic units on Mars does not work well, because of many uncertainties in the temporal character of the geologic units and the lack of temporal continuity among the referents. Also, photogeologic techniques necessarily limit the inspection of material units to surface exposure, and so little is known about their vertical character. Thus stratigraphic columns remain poorly defined. Some of the specific problems include: (1) The base of the Lower Noachian basement material is unexposed and thus remains stratigraphically undefined. (2) Middle Noachian cratered terrain and Upper Noachian intercrater plains materials are intergradational with each other as well as with older and younger units. This means that the ages of parts of the units fall outside the time-stratigraphic positions and periods they are meant to define. Also, the end of the Noachian is commonly viewed as when widespread valley formation and crater degradation largely ceased on Mars. However, some evidence indicates that that cessation may be time transgressive and controlled by elevation [10]. (3) Lower Hesperian ridged plains material is mapped in many areas across the planet, but some patches actually have Late Noachian crater densities [7]. Also, wrinkle ridges deform plains materials in caldera floors and northern plains surfaces, which reminds us that wrinkle ridges are not primary features and thus do not necessarily relate temporally to the materials they deform. Finally, MGS and MO data are revealing that Hesperian Planum itself may be complex stratigraphically. (4) Upper Hesperian complex plains material, representing the Vastitas Borealis Formation likely consists of sedimentary material related to inundation of the northern plains. The unit may represent a very brief moment in geologic time, rather than a truly expansive epoch. (5) The Lower and Middle Amazonian referents are deposits and lobate materials whose detailed histories remain to be determined. (6) The Upper Amazonian flood-plain material in Elysium Planitia now appears to be largely flood lavas that were emplaced in an extremely young and brief event.

Crater-Density Definitions and Precautions. Tanaka [1] used the type material referents to help determine the crater-density boundaries to the time-stratigraphic units, which has been a very useful application of that stratigraphic scheme. However, for stratigraphic applications, crater-density relative-age determinations have some serious limitations that need to be kept in mind. Crater densities provide, assuming no subsequent resurfacing, a mean surface age. Thus, unexposed, older parts of the unit cannot be accurately dated, although in some cases the crater age of buried surfaces can be inferred by the density distribution of large, partly buried craters and depressions indicating possible buried craters. In addition, map units may include outcrops of greatly varying age, in which the crater sample size of individual outcrops may be insufficient to effectively constrain age. Thus, the standard deviation of the mean crater age may be a rather meaningless quantity when it comes to defining the age range of units. An extreme example would be a Hesperian crater density resulting from a map unit that includes individual outcrops of Noachian, Hesperian, and Amazonian material.

Another problem that is increasingly noted is the effects of resurfacing on crater counts. It has long been appreciated that degraded, ancient cratered surfaces on Mars have shown evidence of crater obliteration, both in surface morphology and crater distributions. Also, smaller craters appear to be obliterated at higher latitudes, which may relate to episodic growth and recession of ice-rich dust mantles until geologically recent time [11]. Even at equatorial latitudes, pedestal craters and formation of yardangs in materials including the Medusae Fossae Formation and layered deposits at Meridiani Planum indicate regional scale burial and exhumation. As a result, crater densities in many cases reflect exposure or retention ages that may be much younger than the emplacement age of the material units.

Recommendations for Updating the Formal Stratigraphic Scheme. As previously discussed, some of the referents for defining martian epochs are time transgressive across epoch boundaries, whereas others may represent only a small fraction of the epoch, as defined by crater counts. Because of the utility of crater-count boundaries and all the relative-age determinations that have been performed using the existing scheme, the best option may be to abandon the referent-based, time-stratigraphic approach that has been used, but continue to use the crater-density boundaries defining the epochs for the time being. Eventual updating of the scheme is still desirable, because until then, the association of the time-stratigraphic units with their referents will remain. A better scheme is the modified time-stratigraphic approach used for the Moon, in which significant impact and mare-emplacement events, dated by crater counts and radiometric ages of returned samples, are used as time-stratigraphic demarcations [12]. This scheme developed over time for, as in the case of Mars, rock units were inappropriately used to define time-stratigraphic units initially. To some degree, the lunar approach is bolstered by terrestrial work that appears to support the notion that some significant stratigraphic boundaries such as the Cretaceous/Tertiary may have resulted from impact or other short-lived events.

For Mars, significant widespread and notable events in the geologic record may include large impacts, huge volcanic eruptions, climate change as indicated by extensive high-latitude mantles and in the record of polar layered deposits, and emplacement of huge sedimentary deposits. A specific example is the expansive Vastitas Borealis Formation in the northern plains. This material appears to have been deposited in a geologically very brief span of time. As such, it could be used as an event referent marking the beginning of a “Borealian” Epoch or even Period. A general overhaul of the martian stratigraphic scheme, however, should await updated, systematic, planetwide geologic mapping based on the new MGS and MO data sets and improved mapping techniques discussed herein. (Any drastic changes in Mars stratigraphic nomenclature should be approved among a broad venue of martian mappers and crater counters for formal acceptance.)

Implications. A huge amount of work has already gone into geologic mapping and relative-age dating of Mars for the determination of local to global-scale geologic histories. Nevertheless, significant advances can and will come in how researchers formalize martian stratigraphy and in how well mappers interpret the geologic history of Mars, based on new data, improved techniques, and more thorough crater-density analyses. We recommend that new, planetwide systematic geologic mapping of Mars be undertaken. Moreover, obtaining the best results possible in reconstructing the geologic history of Mars with available data will be vital for intelligently targeting sites to meet the exploration objectives of future Mars missions.

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