THE STRATIGRAPHY OF MARS: WHAT WE KNOW, DON'T KNOW, AND NEED TO DO. K. L. Tanaka, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, ktanaka@usgs.gov;

Introduction: Although the strict formalism of terrestrial stratigraphic nomenclature [1] has been applied to martian schemes, flexibility is also required to accommodate remotely sensed data that vary in type and precision. Invariably, research investigations lead to improvements in data quality, resolution, and interpretation. Therefore, to maintain its utility, the martian stratigraphic scheme must evolve to keep up with the state of knowledge.

For Mars, the first global geologic map, derived from a global image dataset obtained by Mariner 9, formed the basis for defining the Noachian, Hesperian, and Amazonian Periods according to significant geologic map units that seemed to represent major geologic eras [2]. Updated global geologic mapping and crater counts based on improved Viking image data [3] yielded a more detailed scheme that discriminated eight epochs having discrete crater-density boundaries [4]. Now, Mars Global Surveyor (MGS) is providing systematic, detailed topographic data with the Mars Orbiter Laser Altimeter (MOLA) and high-resolution image samples with the Mars Orbiter Camera (MOC), as well as other datasets potentially useful to stratigraphic studies. Is there justification to consider further refinements to the present Mars stratigraphic scheme? What uncertainties remain in documenting and interpreting the stratigraphic record, and how might MGS data help out?

What we know…Geologic mapping and crater counting of Mars has been going on for some three decades, and geologic mapping at various scales using Viking and now MGS data continues [5]. The stratigraphic scheme of Tanaka [4], based on material units and crater counts, generally has survived well the test of other peoples' research, given the difficulties and limitations in documenting and interpreting stratigraphic relations and crater distributions on Mars. The scheme reflects geologic eras dominated by the formation of particular rock units (*referents*) and geologic features. One major problem is that the age of the base of a rock sequence forms the base of a chronostratigraphic unit, in the traditional terrestrial approach. However, for remotely investigated geology, our datable horizon (using crater densities) is actually the unit surface, providing the younger age limit. Moreover, unit surface ages may be *diachronous*, or time-transgressive.

MOC images now permit crater counts of small areas on Mars down to crater diameters of ~20 m [e.g., 6-7]. Access to numerous, small craters generally provides for good statistical precision. Martian crater populations follow a steeper slope for sizes less than about 1 to a few kilometers, consistent with observations for the lunar maria [7-8].

…don't know…The current martian stratigraphic scheme has some inherent pitfalls that make it increasingly inadequate as stratigraphic precision improves. Many of the problems involve the use of geologic-unit referents to define *chronostratigraphic units,* which are units of time representing the emplacement duration of the referents. The martian rock units, however, do not actually span the entire time interval between beginning of emplacement of the referent unit and that of the next younger material referent. Also, the Noachian rock referents are *diachronous,* and some of the younger ones might be. Even if the younger referents have synchronous boundaries (making them *isochronous*), they would not likely by synchronous with other outcrops of similar character. Thus ridged plains material in Hesperia Planum would represent a somewhat different time interval than those in Lunae Planum, and so on. Some problems are more specific to given periods on Mars, as the following shows.

Noachian.. Noachian units were divided into Lower, Middle, and Upper Series on the basis of stratigraphic relations of varying clarity [3]. Because these units consist of rocks of varying age, origin, and modificational state, their stratigraphic character is clearly diachronous. Most of the contacts in the highlands are approximate, because the formational and modificational histories of the units have not been determined in detail and the contacts themselves may be largely obliterated by resurfacing or were gradational to begin with. Generally, the high density of larger diameter craters for Noachian rocks demonstrates their great age. However, local veneers of younger rocks tens to perhaps a couple hundred meters thick would not seriously alter larger crater densities, and Viking images show that such veneers pervade many areas of mapped Noachian rock units.

Hesperian. The ridged plains material of Hesperia Planum serves as the Lower Hesperian Series referent, but many other outcrops of ridged and smooth plains materials of similar appearance occur in the highlands [3]. Although some outcrops may be similar in age to the referent outcrop, others are clearly younger or older [e.g., 3, 9]. Between the Lower and Upper Hesperian Series referents (the latter is the Vastitas Borealis Formation), a considerable period of time may have elapsed. During this interval, a considerable amount of martian geologic activity may have occurred, such as emplacement of the south polar Dorsa Argentea Formation and volcanic sequences in Tharsis and elsewhere [3].

Another concern is the way ridged plains material has been defined. Although wrinkle ridges clearly assist with unit identification, they formed at some time after the material was emplaced. Generally, the ridges appear to be superposed by all larger impact craters and thus formed at virtually the same time as emplacement of the plains material. However, this may not always be the case.

Amazonian. The Lower Amazonian Series referent, smooth plains material in Acidalia Planitia, overlaps in crater density with the Vastitas Borealis Formation and may actually be part of that unit [10]. Overall, geologic activity waned during the Amazonian, and so the Middle and Upper Amazonian Series material referents (plains materials in Amazonis and southern Elysium Planitiae, respectively) represent only brief pulses of activity of uncertain duration. According to two proposed crater chronologies, the Amazonian may cover from nearly 2 to more than 3.5 billion years [4, 7-8]. Thus huge time gaps may occur between the episodes defined by the referent units.

…and need to do. The inadequacies in the current Mars stratigraphic model can be corrected in large degree. Taking the following steps may sharpen our characterization and understanding of Mars' geologic history.

Adopt a referent-free stratigraphy based on crater densities. Defining rock units to be representative stratigraphic referents on Mars has been shown to be problematic. Therefore, I suggest that we continue to use the current *chronologic* system of Periods and Epochs defined by crater-density boundaries in [4], but drop the chronostratigraphic units (Systems and Series) that inadequately define those boundaries. This approach will preserve the extensive relative-age determinations in the literature that have employed the present system. Thus, when geologic mapping, crater counting, and resurfacing analysis refine the crater-density boundaries for outcrops previously used to define chronostratigraphic units, revision of the stratigraphic system will not be required.

Re-evaluate crater distributions. Disagreement still exists over the shape of the crater-production curve [cf. 7-8]. Perhaps careful mapping, improved crater-diameter measuring techniques, and resurfacing analysis will eventually result in a refined production curve for Mars that researchers can agree on. In turn, this would require some modification of the crater-density limits for martian epochs. In any case, the martian epochs can now be calibrated to densities of sub-kilometer craters where saturation has not been reached using the expanded diameter range of crater-production curves.

Use incremental crater-density boundaries. Because of extensive resurfacing on Mars, crater densities at various diameter ranges may represent a combination of ages including that of underlying surfaces, surficial geologic materials, and erosional episodes. Incremental densities can help isolate these different events. Most workers have used $\sqrt{2}$ diameter bins for such analysis [e.g., 6-7, 9, 11].

Subdivide epochs as needed. The four Noachian and Early Hesperian epochs generally seem to be adequate based on stratigraphic needs and chronology, covering the first billion years or so of geologic activity. However, the Late Hesperian and Amazonian cover many diverse geologic events over what may be two-thirds or more of the planet's history. MOC images and potentially future imaging data may make crater counting of sub-kilometer craters a popular and effective stratigraphic approach. Significant periods of outflow-channel development, volcanism, tectonism, and eolian or polar activity may be documented that will serve as justification for subdivision of some Epochs into Stages.

In order to provide a geologic basis for such studies, careful, highly detailed geologic mapping is required. Specifically, instead of grouping large numbers of lava flows, debris aprons, plains deposits, etc. into single geologic units, individual outcrops or a few, closely related outcrops may be mapped as units and crater counted. The geology within high-resolution MOC images will elucidate detail not appreciated in lower resolution Viking and MOC images. For example, some broad plains units of fairly consistent appearance in low-resolution images may be made up of multiple subunits of varying age and surface character apparent in high-resolution images.

Further analysis of martian stratigraphy with new MGS datasets should prove enlightening. We should be able to characterize the history of various events and episodes and answer questions such as: Do broad map units mapped at Viking scales consist of subunits at meter scale? Was geologic activity concentrated in intense, highly sporadic pulses or more spread out over time? What have been the character and relative rates of deposition and erosion in various geologic environments on Mars?

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