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Updating the Planetary Time Scale: Focus on Mars

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Summary

Formal stratigraphic systems have been developed for the surface materials of the Moon, Mars, Mercury, and the Galilean satellite Ganymede. These systems are based on geologic mapping, which establishes relative ages of surfaces delineated by superposition, morphology, impact crater densities, and other relations and features. Referent units selected from the mapping determine time-stratigraphic bases and/or representative materials characteristic of events and periods for definition of chronologic units. Absolute ages of these units in some cases can be estimated using crater size-frequency data. For the Moon, the chronologic units and cratering record are calibrated by radiometric ages measured from samples collected from the lunar surface. Model ages for other cratered planetary surfaces are constructed primarily by estimating cratering rates relative to that of the Moon. Other cratered bodies with estimated surface ages include Venus and the Galilean satellites of Jupiter. New global geologic mapping and crater dating studies of Mars are resulting in more accurate and detailed reconstructions of its geologic history.

Keywords: planets, chronology, stratigraphy, geologic mapping, craters, Mars

Development of the Planetary Time Scale

The formal synthesis of the planetary time scale is a relatively new endeavor, given that it has required space travel. Human and robotic missions to our nearest extraterrestrial neighbor, the Moon, ultimately resulted in the definition and dating of 4 chronostratigraphic periods and 2 epochs (Wilhelms, 1987). This stratigraphic system was based largely on geologic mapping and radiometric dating of samples collected from key, referent lunar surfaces having well-defined crater size-frequency distributions.

Since then, a host of robotic spacecraft missions and analyses have enabled the extension of those results to the dating of other cratered planetary surfaces primarily by assigning them relative cratering rates to that of the Moon (summarized in Tanaka & Hartmann, 2012). This approach also requires an understanding of the evolving populations and locations of asteroids and comets, and the dynamics of impact processes as governed by aspects of both the impacting and target bodies. The most significant progress for extending the lunar chronology to another body has been for Mars, but geologic mapping has also led to proposed stratigraphic systems and divisions for Mercury and Ganymede. Surfaces with low crater densities must be treated cautiously, evidenced by geologic studies of Venus that have led to competing, globally directed (Basilevsky *et al.,* 1997) versus time-transgressive resurfacing histories (e.g., Guest & Stofan, 1999). Recently published mapping results and spacecraft observations of the Galilean satellite Io spanning decades indicate that volcanic processes resurfaced regions of the body on time scales of years to millions of years (Williams *et al.*, 2011).

The solid surfaces of asteroids and other satellites of Jupiter, Saturn, Uranus, and Neptune show varying degrees of cratering that reflect surface ages. While asteroids are commonly saturated with craters, indicating their primordial origin, some asteroids, comet nuclei, and other bodies demonstrate later resurfacing as their rocky or icy crusts evolved. Geologic mapping, crater counting, cataloguing of asteroids and comets using Earth-based telescopes, theoretical studies, scientific instrument development, and robotic spacecraft missions continue to be supported by government-sponsored research and technology programs in a large number of countries.

Advancement in Mars Mapping

The Red Planet has a geologic character similar to the Moon, with vast expanses of cratered terrain and lava plains, but with the important addition of features resulting from the activity of wind and water over time. This results in a geologically complex surface history; geologic mapping has assisted in unraveling it, following the approaches developed for studies of the Moon. Beginning in the 1970s with Mariner 9 and Viking, and continuing with a flotilla of additional orbiters and landers beginning in the 1990s, Mars has become a highly investigated planet.

Global geologic maps of Mars have provided the basis for the major milestones in reconstructing the stratigraphy and geologic history. The first map by Scott & Carr (1978), based on Mariner 9 spacecraft images at 1-2 km spatial resolution, formed the basis for dividing the surface into the Noachian (oldest), Hesperian, and Amazonian (youngest) Periods. The Viking mission later provided images of the planet at an order-of-magnitude improved spatial resolution, leading to a revised global geologic map (Scott *et al.,* 1986-87). Furthermore, this map established the basis for dividing the three chronostratigraphic periods into eight epochs, whose boundaries were defined by crater densities (Tanaka, 1986).

A third generation geologic map (Tanaka *et al., in* review a) is the first to take advantage of laser altimeter-derived global topography, as well as various unprecedented resolutions of imaging, spectral, and radar-sounding data sets. These data allow more accurate mapping, which has been enhanced by consistent application of stratigraphic mapping techniques and digital mapping tools unavailable during previous global mapping efforts. The mapping integrates cumulative advancements in understanding of Mars geologic history via many process and compositional studies. In stride with advancements in data return and mapping techniques, resources for crater dating have also improved to permit both detailed crater dating of type surfaces down to diameters of ~100 m (Platz *et al., in* review) as well as global, generalized crater counts for diameters down to 1 km (Robbins & Hynek, 2012). This effort provides the first synopsis of the surface ages of the planet in which each outcrop has documented crater density information (Fig. 1).

Major findings of this effort include recognition that the earliest geologic record on Mars – the Early Noachian Epoch – is substantially more represented on the surface than previously recognized (Tanaka *et al., in* review b). Crater depth-diameter ratios are similar for Early and Middle Noachian surfaces, and craters were obliterated more so at lower elevations in Noachian rocks. These results indicate that Noachian resurfacing was spatially complex, long-lived, and gravity-driven and dominated by fluvial and aeolian erosion and volcanic flows (Irwin *et al.*, *in* press).

Outlook

Ongoing and future spacecraft exploration, telescopic observations, meteorite studies, instrument development, and data analysis will lead to further refinements in and broadening of the planetary time scale. NASA's MESSENGER spacecraft is currently imaging the Mercurian surface, half of which was previously unobserved. Documentation of cratering histories of planetary objects in the outer solar system will be further enhanced in 2015 by spacecraft reaching the never-before-visited Pluto system by NASA's New Horizons mission and the largest Main Belt asteroid Ceres by NASA's DAWN mission.

Developing techniques and databases will provide new approaches for estimating cratering rates on solar system bodies, including (1) detailed surveys of the sizes and trajectories of asteroids and comets, and (2) for Main Belt asteroids, radiometric ages of large impact events inferred from meteorite studies to correspond to resurfacing events of spectrally associated asteroid surfaces as suggested for Vesta. Mars sample return as encouraged by the U.S. National Research Council (Committee on the Planetary Science Decadal Survey, 2011) and/or development of remotely operated radioisotopic dating apparatus (Anderson *et al*., 2012) may begin to provide direct age determinations of extraterrestrial surfaces in the coming decades.

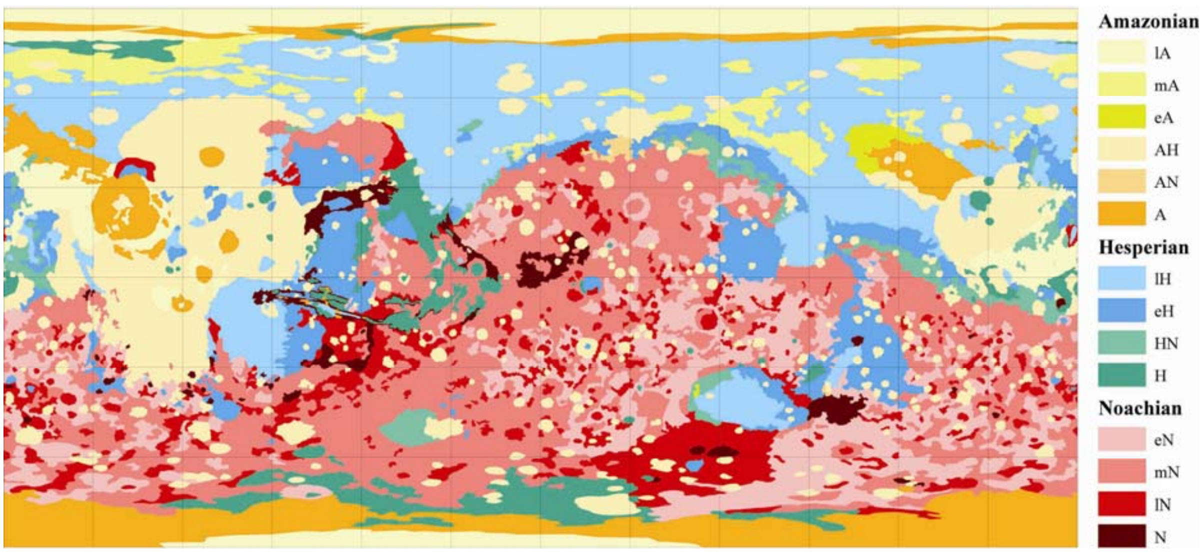

Fig. 1 – Chronostratigraphic map of Mars (from Tanaka *et al., in* review b).

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