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THE MARTIAN STRATIGRAPHY - SHORT REVIEW AND PERSPECTIVES

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Abstract. The main aspects of the Martian stratigraphy have been determined from the detailed study of Mariner 9 and Viking Orbiter images. Three major stratigraphic systems, the Noachian System, the Hesperian System, and the Amazonian System, are inferred from these studies. The global geological evolution of Mars is essentially derived from its stratigraphy. It reveals that tectonism and volcanism were widespread during two major periods (Noachian and Lower Hesperian) and became more localized during the Upper Hesperian and Amazonian periods. The transition between these two major periods occurred about 2 Ga ago, and significant geologic activity could still be present. However, a number of geologic features and processes remain little understood. Future investigations, including complete high resolution imaging and detailed mapping, geochemical mapping, in situ chemical analyses, etc., will be necessary in order to improve our knowledge of the Martian stratigraphy and geologic evolution and are essential to prepare any future Mars Sample Return mission and the Human Exploration of this planet.

1. Brief Review of *the State of the Art*

1.1. STRATIGRAPHIC DIVISIONS

In an early study of the Martian surface, Soderblom *et al.* (1974) identified four stratigraphic divisions: ancient eroded uplands, cratered (ridged) plains interpreted as being volcanic, Elysium volcanic rocks, and Tharsis volcanic rocks. A formalized stratigraphy was first presented by Scott and Carr (1978). Condit (1978) determined the relative ages of map units. These units were classified and placed in three stratigraphic systems: the Noachian System (rugged and heavily cratered material), the Hesperian System (ridged plains material), and the Amazonian System (relatively

TABLE I

Chronostratigraphic series and referents for Mars (Tanaka, 1986)

Series	Referent
Upper Amazonian	Flood plains material, southern Elysium Planitia
Middle Amazonian	Lava flows, Amazonis Planitia
Lower Amazonian	Smooth plains material, Acidalia Planitia
Upper Hesperian	Complex plains material, Vasistas Borealis
Lower Hesperian	Ridged plains material, Hesperia Planum
Upper Noachian	Intercrater plains material, east of Argyre Planitia
Middle Noachian	Cratered terrain material, west of Hellas Planitia
Lower Noachian	Basement material, Charitum and Nereidum Montes

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smooth, moderately cratered plains material and polar deposits). The stratigraphic system boundaries were defined by using densities of craters (Greeley and Spudis, 1981; Scott and Tanaka, 1984, 1986). Tanaka (1986) proposed a more detailed chronostratigraphic classification system. He subdivided the chronostratigraphic systems into series, series names being adapted from system names and qualified with *Upper*, *Middle*, and *Lower* (Table I). These new series were largely defined by their surficial characteristics, and rock types were inferred.

The inferred events of the Martian Series were presented and discussed by Tanaka (1986). They are summarized as follows:

1. Lower Noachian	Major impact basin formation and formation of the northern lowlands.
2. Middle Noachian	Cratered terrain formation.
3. Upper Noachian	Intercrater plain resurfacing, reduced cratering flux, intense erosion and runoff channel development, beginning of intense faulting (Syria Planum), formation of highland volcanoes and ridges.
4. Lower Hesperian	Ridged plains emplacement, burial and degradation of lowland cratered terrains, extensive faulting (Syria Planum), major rifting (Valles Marineris) and volcanism (Alba Patera).
5. Upper Hesperian	Resurfacing of northern plains by complex of lava flows, eolian deposits, and alluvial sediments, then erosion of these plains, major volcanism (Tharsis Montes, Alba Patera, etc.), outflow channel development by water flooding, deposition of Valles Marineris layered deposits, waning tectonism (Tharsis), deposition of southpolar unconsolidated material;
6. Lower Amazonian	Lava flows form northern smooth plains, local volcanic flows (Tharsis Montes, Alba Patera, Elysium Mons), formation of Olympus Mons aureoles.
7. Middle Amazonian	Continued accumulation of lava flows in northern plains, volcanism at Tharsis Montes and Olympus Mons, landslides in Valles Marineris.
8. Upper Amazonian	Formation of broad flood plains in southern Elysium Planitia, youngest lava flows at Tharsis Montes and Olympus Mons, most recent resurfacing of northern plains, reworking of polar layered, dune, mantle, and ice deposits into present form, landslides at Olympus Mons and in Valles Marineris.

1.2. ABSOLUTE AGES OF THE STRATIGRAPHIC UNITS

Several models have been made to determine absolute ages of Martian stratigraphic units; they remain a subject of controversy. The models allow the prediction of the relation between crater density and absolute age of Martian units based on (1) the same relation derived for lunar rocks from sample data, and (2) the ratio of the cratering fluxes of Mars and the Moon. Because these factors are not precisely determined, estimates of crater production rates for Mars differ considerably. Two dominant crater chronology methods were proposed by Neukum and Wise (1976) and by Hartmann *et al.* (1981), respectively. Differences of a factor of two in relative crater production rates between the two methods create quite different chronologies for the Martian epochs. The major uncertainty in the Neukum and Wise model is the age of the Martian highlands. Consequently, most geologic activities (within the Noachian and Hesperian periods) occurred either during the first Ga (Neukum and Wise, 1976;

Neukum and Hiller, 1981) or during the first two Ga (Hartmann *et al.*, 1981). Another absolute age model (Soderblom *et al.*, 1974) suggests crater flow history intermediate between the models from Neukum and Wise (1976) and Hartmann *et al.* (1981).

2. Future Developments and Expected Results from Future Non-Sample-Return Missions

One of the scientific objectives of future Mars missions will be to characterize the chemical and mineralogical composition and the absolute ages of the Martian stratigraphic units.

Knowledge of the type and the chemical composition of the minerals and the texture and modal composition of the sediments and rocks in which they occur, is fundamental to the understanding of the basic properties of Mars and the global geological processes during its evolution. These include early differentiation, composition of the ancient crust and mantle, magmatic evolution, impact metamorphism of the ancient crust, weathering processes leading to transport and sedimentation of surface materials, and the global distribution of volatiles and of various types of sediments.

The study of the composition of surface rocks and soils on Mars is complicated by the great variety of physical and chemical processes that have shaped the Martian surface. The composition of the surface materials imposes stringent constraints on the interior, and geophysical data will define the volume and the physical state of the crust, the mantle and the core. Determination of the chemical composition of the crust and mantle depends primarily on samples and their mineralogical texture, chemistry, and isotopic properties. With these analyses, the history of the rocks through volcanic, metamorphic, sedimentary, impact, and weathering processes can be studied. These type of investigations can only be conducted on samples returned from the planet for study on Earth. However, remotely sensed chemical and mineralogical data can be obtained at resolutions that are sufficiently high to indentify regional geochemical trends, and thus provide a basis for the planet wide extrapolation of sample data. In order to fill the gap between the broad capabilities of orbital mapping and the local data obtained from sample studies, surface chemical investigations should be made. Beside the techniques usable from orbit, which also can be applied at the surface, *in situ* compositional analyses could provide broader chemical coverage by applying, e.g., proton alpha scattering spectrometry, X-ray fluorescence, X-ray diffraction.

Preliminary chemical characterization of surface materials was performed by orbital IR spectrometry, thermal imaging and gamma ray spectrometry over selected Martian regions during the USSR Phobos 2 mission (Bibring *et al.*, 1989; Bibring *et al.*, 1990; Selivanov *et al.*, 1989; Surkov *et al.*, 1989; d'Uston *et al.*, 1989). During the Mars Observer Mission (USA), global elemental composition of surface materials should be provided by gamma-ray spectroscopy. High spectral resolution mapping coverage in visible and near IR wavelengths should provide mineralogic characterization of surface materials during the Mars-94 mission (USSR). However, *in situ* chemical analyses of several significant stratigraphic units will have to be performed in order to substantiate the orbital data. Because of the geographic distribution of the stratigraphic units to be analyzed, it will be necessary to establish a network of small stations (soft, semi-hard, or hard landers) on the surface of Mars. Various sensors could provide geochemical information on surface materials in addition to geophysical data. Such type of mission, which is foreseen by NASA possibly by the end of this century, is also studied by ESA (MARSNET project) within the framework of its medium size mission planning cycle (*blue mission* of Programme HORIZON 2000). Should this project be accepted, it could be a significant European contribution to an international network of scientific stations on the surface of Mars. It would be appropriate to use the leading time for the development of advanced miniaturized geochemical and chemical instruments.

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