Martian Chronology: Goals for Investigations from a Recent Multidisciplinary Workshop. P. T. Doran[1], T. E. Cerling[2], S. M. Clifford[3], S. L. Forman[1], L. Nyquist[4], D. A. Papanastassiou[5], B. W. Stewart[6], N. C. Sturchio[1], T. D. Swindle[7], [1]Earth Environmental Science (MC 186), University of Illinois at Chicago, Chicago, IL 60607-7059, [2]University of Utah, Department of Geology & Geophysics, Salt Lake City, UT 84112, [3]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston TX 77058, [4]NASA Johnson Space Center, Houston, TX 77058, [5]Jet Propulsion Laboratory, Caltech, Pasadena, CA, [6]Department of Geology & Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260, [7]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721.

Introduction: The absolute chronology of Martian rocks and events is based mainly on crater statistics and remains highly uncertain. Martian chronology will be critical to building a time scale comparable to Earth's to address questions about the early evolution of the planets and their ecosystems. In order to address issues and strategies specific to Martian chronology, a workshop was held, 4-7 June 2000, with invited participants from the planetary, geochronology, geochemistry, and astrobiology communities. The workshop focused on identifying: a) key scientific questions of Martian chronology; b) chronological techniques applicable to Mars; c) unique processes on Mars that could be exploited to obtain rates, fluxes, ages; and d) sampling issues for these techniques. This is an overview of the workshop findings and recommendations.

Table 1. Martian epochs and their model ages [1].

Epoch	Maximum age (Ga)
Early Noachian	4.6
Middle Noachian	~4.5 to 3.92
Late Noachian	~4.3 to 3.85
Early Hesperian	3.8 to 2.5
Late Hesperian	3.7 to 1.3
Early Amazonian	3.55 to 0.6
Middle Amazonian	1.8 to 0.25
Late Amazonian	0.5 to 0.1

Scientific Questions (chronologic targets).

Calibrating the long-term Mars cratering rate. To calibrate the Martian cratering rate and improve chronology based on crater statisitics, the most critical date to acquire is Hesperian to middle Amazonian. Additional Noachian and late Amazonian dates should be acquired to check for changes in the cratering rate over time. Desirable units for dating are igneous rocks having pristine cratering records (i.e., unbrecciated). By dating the largest impacts on the planet (e.g., Hellas), absolute global time horizons may be established.

Major volcanic events. Volcanic flows are probably the best types of deposits to constrain the impact cratering rate. It is important to establish the ages of volcanic features and address questions regarding the timing and long-term trends in global volcanic activity which may be related to the fluvial events discussed below. Chronologic and related isotopic information on the oldest volcanic rocks may provide insight into early planet-wide processes, such as core formation, crust-mantle differentiation, and the possibility of plate tectonics, early in Martian history.

Ancient and recent fluvial activity. While most hydrologic activity on Mars is thought to be ancient (pre-Amazonian), high-resolution MOC images suggest recent fluvial activity on the surface of Mars (<10^7 a BP) as well [2]. Hypotheses invoking changes in Mars obliquity [3] and internal processes [4] have been put forth to explain how liquid water might be generated on the surface during the present epoch. Discrimination between these possible origins will require both *in situ* confirmation of their true nature and accurate dating of their occurrence. Data on the history of surface water on Mars would help constrain the environmental conditions during the Noachian, which in turn would help constrain models for prebiotic chemistry, protobiology, the possible origin and evolution of life, and the potential transfer of life between Mars and Earth.

Polar layered terrain. As the planet's principal cold traps, the Martian polar regions have accumulated extensive mantles of ice and dust that cover ~10^6 km^2 and are as much as 4 km thick [5]. The scarcity of superimposed craters on their surface suggests that these deposits are relatively young (<10^8 a). Their layering allows for a temporal calibration of global events (e.g., volcanic eruptions, dust storms, large impacts, etc.) that can be used as chronological markers elsewhere.

Chronology Techniques Applicable to Mars.

Nuclear techniques. Radiogenic dating by the K-Ar system (including ^{40}Ar-^{39}Ar) will be applicable to the >10^5 a window for dating volcanic lava flows or widespread ash deposits (e.g., in the polar layered terrain). An application of radiogenic dating to the history of water on Mars is the use of the K-Ar or Rb-Sr methods to date evaporite deposits, especially K-rich salts, and possibly co-existing carbonates. Radioactive parent-daughter dating schemes will be directly applicable (K-Ar, Rb-Sr, Sm-Nd, U-Th-Pb, Lu-Hf, Re-Os, and short-lived systems, e.g., Hf-W, Mn-Cr, I-Xe, Pu-Xe, ^{146}Sm-^{142}Nd). If there is recent (<10^6 a) activity on Mars, U-Th decay series methods can be used to determine the: a) ages of young lava flows or pyroclastic deposits; b) ages of waterlain spring deposits, evaporites, and hydrothermal deposits/alterations; and c) atmospheric residence times of aeolian particulates.

Cosmogenic techniques. The production rates for cosmogenic nuclides on Mars will allow for exposure dating of samples within the 10^7 a range. Events and processes that may be datable using cosmogenic nuclides include: a) erosion (i.e., by floods, landslides, glaciation); b) deposition age of previously deeply buried material (erosion and deposition by glacial processes, floods, etc); c) faulting (tectonic scarps); and d) volcanic or impact events. The history of aeolian dust may also be measurable, allowing trapped dust in the polar layered deposits to be dated. The use of secondary neutron capture effects (e.g., in Gd, Sm) would permit the extension of studies of cosmic ray irradiation to the 10^9 a scale.

Luminescence dating. Luminescence dating techniques have been used successfully on terrestrial aeolian and fluvial deposits. On the Earth, during burial, minerals absorb natural radiation from isotopes of U, Th, and K, and from cosmic rays. The absorbed radiation leads to a metastable concentration of electronic charge "trapped" at defect sites within the minerals' crystal lattice. The trapped charge is proportional to the absorbed radiation dose and can be determined by induced fluorescence. Luminescence techniques for Mars require consideration of: a) the higher cosmic ray flux; b) uncertainties in the mineralogy of Mars materials; and c) the effects of extremely cold temperatures. Windblown sediments may be suitable for dating in the $<10^5$ a range. The greatest potential for this technique would be *in situ* use in the polar layered terrain.

Mars-specific chronometers.

Stable isotopes of nitrogen. The unique isotopic composition of nitrogen in the Martian atmosphere may permit a Mars-specific "chronometer" for tracing the time-evolution of the atmosphere and of lithic phases with trapped atmospheric gases. Theoretical models predict a nearly linear increase of $\delta^{15}N$ from near zero to the present-day value of ~620‰ [6, 7]. The time rate of change of $\delta^{15}N$ could be calibrated by measuring $\delta^{15}N$ in nitrogen extracted from secondary phases of rocks (e.g., impact glass) with ages measured by standard radiometric techniques. Subsequent measurement of $\delta^{15}N$ in a nitrate, for example, would determine the time of nitrate deposition. The secular variation in the isotopic compositions of other atmospheric gases (O, C, H, Ar) also could be used to determine independent estimates of the deposition time.

Gas Fluxes. The goal of flux investigations is to establish the rates of volatile transfer from the Martian crust to the atmosphere, most likely by molecular diffusion. Data on volatile species, such as He, Rn, CO_2 and H_2O, can then be used as a prospecting tool to define areas of recent hydrologic processes (deep saline ground water or trapped hydrothermal fluids).

Platinum Group Elements (PGE). Measuring the abundance of PGE in Martian soils would provide a measure of the accumulated influx of micrometeorites to the Martian surface. The initial component of Martian PGE should have been partitioned into the core at its formation. The lack of crustal recycling on Mars would allow the accumulation of PGE on the Martian surface over long periods. The effects can address surface (regolith) gardening by meteorite impacts.

Recommendations. The workshop focused on key science questions and solutions. General recommendations on sampling were made:

Context and background. For useful chronometric information, it is essential to know the geological (stratigraphic) context of the samples. Knowing the chemistry of the samples is also critical for most applications. In addition, there are certain baselines that need to be known, such as the present composition of the atmosphere (and trace species of interest) and the chemical and physical characteristics of current dust.

Multiple techniques. For any chronometric determination, an age on a single sample determined by a single technique is unlikely to be useful. For full confidence in the results, it is preferable to measure ages by multiple techniques on multiple samples. If a single technique is to be used (e.g., in situ), it must be shown to give consistent results on multiple samples.

Technique development. Most of the techniques described require further development for use on Mars. For *in situ* sampling, funds must be committed early enough to allow for design, miniaturization and thorough testing and calibration. For a sample return mission, questions of environmental requirements for the samples and planetary protection must be considered.

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