MEASUREMENTS OF COSMOGENIC NUCLIDES IN AND THEIR SIGNIFICANCE FOR SAMPLES RETURNED FROM MARS.
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Introduction: Sample return missions enable the use of state-of-the-art scientific equipment and techniques in labs on terra firma to investigate extraterrestrial samples. The Genesis and Stardust missions are excellent examples of the scientific yield made possible by sample return. The availability of even a small amount of sample allows complementary multiple techniques to be applied to the same sample and in many instances duplicate measurements can also be made. The importance of sample return for Martian chronology in particular was reviewed [1].

Cosmogenic nuclides (CNs) are produced by cosmic-ray nuclear interactions with target nuclei in rocks, soils, ice, and the atmosphere. CNs have been widely used for the investigation of solar system matter for several decades [e.g., 2]. Concentrations of stable nuclides, such as ^{3}He, ^{21}Ne, and ^{38}Ar, may grow monotonically over time as the target material is exposed to cosmic rays. The concentrations of cosmogenic radionuclides, such as ^{10}Be, ^{26}Al, and ^{14}C also build up with exposure time but reach saturation values after several half-lives.

Especially since the advent of accelerator mass spectrometry (AMS), CNs in terrestrial samples have been routinely used to study the timing of glaciation, surface erosion rates, subduction rates, and atmospheric and ocean circulation [e.g., 3]. CNs on Mars will be able to answer questions about crater ages, cosmic-ray exposure ages, erosion rates of rocks and surface materials, tectonic events, and deposition rates of sediments and/or volatiles. The concentrations of cosmogenic stable nuclides give the integrated exposure time of the target rock/mineral, and the activities of radionuclides give recent records of exposure for times up to a few half-lives.

Cosmogenic Nuclides on Mars: Unhindered by either a substantial atmosphere or a planetary magnetic field, galactic cosmic rays (GCR) readily reach the Martian surface at a rate much higher rate than on Earth. The CN production rates and depth profiles on the Martian surface are similar to those on the Moon, even after taking into account the average Martian atmospheric depth of ~15 g/cm^2, which removes mainly the much lower-energy solar cosmic rays. The production rates of various CNs on Mars have been calculated using the LAHET Code System that has been well tested using a database of CN observations in lunar, meteoritic, and terrestrial samples. These results show that the production rates of CN on Mars are 3 orders of magnitude higher than those on the Earth's surface and similar to those in meteorites and lunar samples. Consequently many CNs should be measurable in Martian surface samples.

The applications of CNs on Mars will be similar to terrestrial applications related to landscape evolution that include: erosion and exposure histories (glaciation, floods, landslides, and faults); ages of impact craters; deposition or ablation rates of soils and icecaps; and ages of young volcanic eruptions. On Mars, the determination of 'modern' steady state erosion rates of bedrock surfaces may give information on long-term erosion rates of the surface. The histories of aeolian dust and layered terrains near the poles can also be studied. The use of multiple CNs will be required to constrain exposure histories of Martian surface samples.

Table 1. Selected cosmogenic nuclides made on Mars.

Nuclide	Half-life (yr)	Major targets
^{54}Mn	0.855	Fe
^{22}Na	2.61	Mg, Si
^{60}Co	5.27	Co
^{14}C	5,730	O
^{41}Ca	1.04×10^5	Fe, Ca
^{81}Kr	2.3×10^5	Sr, Y, Zr
^{36}Cl	3.01×10^5	Cl, K, Ca, Fe
^{26}Al	7.05×10^5	Mg, Al, Si
^{10}Be	1.36×10^6	C, O, Mg, Si
^{53}Mn	3.7×10^6	Fe
^{129}I	1.57×10^7	Te, Ba, REE
^{3}He	Stable	O, Mg, Si, Fe
$^{20-22}$Ne	Stable	Mg, Si
^{36,38}Ar	Stable	Ca, Fe
^{150}Sm	Stable	^{149}Sm
^{158}Gd	Stable	^{157}Gd

Some CNs of particular promise for unraveling the histories of Martian surfaces are listed in Table 1 along with their half-lives and the major target elements from which production occurs. They are often used in combination with one another. For example, the ^{21}Ne-^{10}Be-^{26}Al combination is a powerful one for solving complex exposure histories of both terrestrial surface morphologies and histories of meteorites. However, given the present detection methods and limits these important CNs can only be measured in returned samples.

Issues Addressed by Measurements of Cosmogenic Nuclides: An important objective of Martian chronology studies is to construct a timeline for the evolution of the planet.

Absolute age of impact craters. At present, the absolute chronology of Mars is based on scaling a cratering rate established for the Moon by dating of returned lunar samples. However, uncertainties of the scaling relation create large uncertainties on Martian chronology [e.g., 4]. Absolute age measurements of a few critical craters would permit calibration of a long-term cratering flux rate on Mars and its use as a planet-wide dating tool. Based on results for meteorites (asteroidal) and lunar samples, we anticipate that Martian surface materials have been exposed to cosmic rays for only a small fraction of the age of the solar system. Ejection by an impact is one mechanism (volcanism and surface erosion or ablation are others) for excavating deep-lying material, and thereby starting the cosmic-ray clock. The exposure ages of impact ejecta provide an absolute determination of a crater's age (e.g., South Ray and North Ray Craters on the Moon and Meteor Crater on Earth). Analogous information for a Martian crater would provide a crucial, absolute calibration point for relative terrain ages obtained by crater counting.

Surface exposure ages and erosion rates. The Martian surface is also modified by wind, flood, glaciation, and landslides. CN concentrations and ratios reveal the timing and rate of such events. Micrometeorite milling erodes lunar samples at rates of ~mm/Myr. Wind-blown dust particles also erode (and may bury) surface features. Erosion rates on Mars are not well constrained, but will fall naturally out of modeling calculations, where they appear as necessary parameters in the deconvolution of CN depth profiles and activity ratios.

Regolith gardening. The rate of gardening (overturn and mixing by meteorite impact) in a regolith can be inferred by comparing the depth profiles of CNs in short cores [5]. Deeper-scale gardening processes can be deduced by comparing the depth profiles of CNs that are produced by thermal neutron capture but have different half-lives. Good candidates for such measurement are radioactive ^{41}Ca, ^{60}Co, and stable ^{156,158}Gd and ^{150}Sm. The study of Martian ^{14}C has been proposed as a way to probe the nature of atmosphere-regolith interactions [6]. However, the Martian atmosphere is thin so production of ^{14}C from soil nitrogen, and perhaps even oxygen could complicate any interpretation [7]. Nevertheless, ^{14}C will be produced and deposited on surface materials and its presence is potentially a tracer for chemical reactions occurring in the regolith.

Ice cap evolution. Ratios and concentrations of two or more CNs with different half-lives measured in rock fragments in the ice cap will provide average ice accumulation or sublimation rates. CNs in ice will also constrain ice transport histories.

Sampling Requirements for Mars Sample Return:

Sample Size. Although masses needed for measurement of CNs vary for the nuclides listed in Table 1, meteoritic and lunar samples weighing 10-100 mg usually suffice. For micrometeorites, we have measured ^{10}Be and ^{26}Al in individual particles weighing ~10 μg [8]. Noble gas measurements in cosmic spherules have been reported [e.g., 9]. However, measurements of ^{129}I, ^{41}Ca, or ^{14}C in samples of less than 1 mg are impossible with the present detection limits. With current technology, the most promising approach for small samples will be to measure the cosmogenic noble gases and the radionuclides ^{36}Cl, ^{26}Al, ^{10}Be, and ^{53}Mn. Although we do not know how much mass early Mars sample return missions will bring back, the amounts may will almost certainly be smaller than the Apollo missions returned. A few tens of μg of sample would enable us to measure 3-4 CNs with less than 10-20% uncertainty, although the precision will depend on the specific exposure history of the material. If a larger sample is available, measurements of both stable and radioactive CNs could be made for samples taken from depths of up to ~3 m depending on the details of the irradiation. At greater depths, the production of CNs is likely to have been too small to measure.

Sample handling. Cosmic ray exposure geometry is needed to calculate exposure histories. Documentation of the sample setting before, during, and after sampling will be required. The documentation of Apollo astronauts is a good model. The irradiation of the samples during the return trip to Earth raises additional complications [10]. Large solar particle events and GCR particles could produce short-lived radionuclides such as ^{54}Mn, ^{22}Na, and ^{60}Co at levels comparable to those present at the time of sample collection. As massive shielding of the return capsule is not feasible, and would increase rates for GCR-induced reactions, some means for monitoring the production of CNs should be included in the design of the mission.

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