COSMOGENIC NUCLIDES IN THE INNER SOLAR SYSTEM: SURFACE EXPOSURE AGES FOR MARS AND ASTEROID 25143 ITOKAWA

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INTRODUCTION
As shown by the papers of this issue of Elements, cosmogenic nuclides have a great deal to tell us about the physical setting and duration of a sample’s exposure to cosmic rays. For a terrestrial sample, a path leads from the exposure history to a better understanding of the evolution of the Earth’s surface through time. For an extraterrestrial sample, our focus here, the path may lead to a better understanding of major asteroidal collisions, transport times from the asteroid belt to Earth, and even solar flare activity.

The potential importance of the cosmogenic nuclides was well understood in the 1950s. The difficulties related to detection were daunting, though, and the early studies, especially of terrestrial materials, heroic in scale. Meteorites make an easier target for study. Most of them record and preserve the by-products of cosmic ray interactions at much higher levels than do Earth’s surface materials. The higher levels derive in part from the fact that meteoroids, the spacefaring precursors of meteorites, have neither a substantial atmosphere nor a strong magnetic field to screen out cosmic rays as they orbit the Sun. In the years between 1960 and 2000, literally thousands of measurements were made of cosmogenic nuclides in meteorites. Alongside this body of data grew an interpretive framework of modeling calculations, which was supported by advances in computers and extended compilations of nuclear data. Much of this work is reflected, either directly or indirectly, in today’s terrestrial research.

The study of cosmogenic nuclides in meteorites continues apace, having greatly benefited from the same improvements in measurement technology that have nurtured the explosion of terrestrial studies. Meteorites, however, are no longer the only items on the menu of extraterrestrial materials available for study. A first big bump came with the return of the Apollo and Luna samples and another with the ability to analyze tiny cosmic spherules, which are the main source of extraterrestrial material landing on the Earth today. Human activity in space has recently brought samples of Mars and of an asteroid within experimental reach. In keeping with the spirit of this issue of Elements, we summarize some results concerning cosmic ray exposure histories of material from Gale Crater, Mars, and from the asteroid Itokawa.

EVOLUTION OF A MARTIAN SURFACE
Rapid, wind-driven erosion 78 million years ago may have exposed the surface of a Martian mudstone to cosmic rays.

The Mars Science Laboratory (MSL) landed on Mars on August 5, 2012, at the foot of a layered mountain within Gale Crater (5.2° S, 137.3° E). The mission rover, Curiosity, was deployed in an area named the Yellow Knife formation, which includes rocks that probably formed by the deposition of waterborne sediments. Curiosity picked up and analyzed a small sample of one local rock, the “Sheepbed mudstone.” The main goal was to obtain a $K$-$^{40}Ar$ age, but with the determination of $^{40}Ar$, the concentrations of the noble gases $^{3}He$, $^{21}Ne$, and $^{36}Ar$ came as a bonus. From the concentrations of the cosmogenic components, the MSL team deduced a history of cosmic ray exposure for the mudstone.

Among several scenarios considered, Farley and coworkers (2014) prefer one in which the sediments were first rapidly deposited and swiftly buried to a depth penetrated by very few cosmic rays. There the rock remained until 78 million years ago, when wind erosion quickly stripped away enough of the overburden for the accumulation of cosmogenic nuclides to begin in earnest. The calculated exposure age of 78 Ma is old by the standards of the terrestrial surface, but much younger than the estimated $K$-$^{40}Ar$ age of the rock itself, which is over 4 Ga. The MSL authors interpret the exposure age in the context of a Martian landscape in which winds from the northeast prevailed (Fig. 1). Scouring by wind over time led to “scarp retreat” at a rate of ~75 cm/My over the relatively soft regions that include the Sheepbed mudstone (Fig. 2).

The duration of surface exposure has some implications for the search for organic materials on Mars. Cosmic ray protons and their nuclear by-products have more than enough energy to destroy chemical bonds and to convert organic compounds with higher molecular weights to compounds with lower ones. When prospecting for unaltered Martian organics, therefore, rocks with lower doses of cosmic rays are preferred. Farley and coworkers argue that samples taken closer to the retreating scarp may have lower radiation doses and would be good material to analyze.

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ADAPTED FROM FARLEY ET AL. (2014)
ITOKAWA 25143: LIFE EXPECTANCY OF AN ASTEROID

The Itokawa regolith is young—evidently life is short for a particle on the surface of a rubble pile.

The Japanese space probe Hayabusa 1 (Fig. 3) was launched in May 2003 and headed for the S-type asteroid Itokawa 25143. Earlier, remote determinations of the asteroid had shown Itokawa to be a rubble pile, a heap of fragments that have stayed together or perhaps were reassembled in the wake of a violent collision between two objects. The main objective of the mission was to fire tiny pellets at the asteroid’s surface, to collect the asteroidal particles ejected, and to return them to Earth. However, sample collection did not go as planned. Apparently the pellet gun misfired, and what little material that found its way to the sampling container was stirred up from the low-gravity surface by the landing of the spacecraft itself. The trip home was difficult, but the retrieval of the return capsule from the Australian outback went smoothly. After intensive efforts involving Moon suits and small brushes, the Hayabusa team recovered from the sampling container a dusting of several thousand tiny particles—the first ever to have been returned from an asteroid through human agency (Fig. 4).

Mineralogical and elemental analyses led quickly to the conclusion that Itokawa resembles LL chondrites, one of the commonest types of meteorite. Nagao et al. (2011) measured the concentrations of the light noble gases in three of the particles, which included not only cosmogenic contributions but also He, Ne, and 36,38Ar implanted by the solar wind. Solar wind ions have such low energy that they cannot pass through more than a few micrometers of matter. Thus, the presence of the solar gas offered strong, if circumstantial, evidence that the particles were recently at the asteroid’s surface. Although the solar gases made it difficult to resolve the cosmogenic 21Ne, Nagao and coworkers were able to set an upper limit on its concentration. Subsequently, Meier et al. (2014) were able to resolve cosmogenic 21Ne in three more Itokawa grains.

To obtain an exposure age, one needs to measure the concentration of 21Ne, that is, not only the number of atoms in a sample but also its mass. Both Nagao et al. (2011) and Meier et al. (2014) obtained the number of 21Ne atoms with a mass spectrometer. For the purpose, Meier and colleagues used an instrument with a very high sensitivity for He and Ne. Interestingly, neither group weighed the particles, which could have risked loss through handling and/or exposure to the terrestrial atmosphere. Instead the masses of the particles were calculated the long way around, from their volumes, determined by synchrotron radiation X-ray tomographic microscopy, and from their densities, which Nagao adopted from other work and Meier et al. inferred from Raman spectroscopy. One grain analyzed by Meier et al. yielded an exposure age of about 1.5 million years; less precise ages for the other grains are compatible with this number.

Remarkably, all six Itokawa grains analyzed so far contain one to three orders of magnitude less cosmogenic noble gases than typical lunar regolith particles. Nagao et al. (2011) interpreted the low 21Ne concentrations in terms of rapid erosion of the Itokawa regolith—at a rate tens of centimeters per million years—as one might expect on a body with very low gravity. So if, and such high erosion rates persist, Itokawa will disappear entirely in a few hundred million years, in agreement with survival-time estimates for asteroids of its size (Bottke et al. 2005). Other interpretations are possible, however. The age calculations assume that the 21Ne was produced at the surface of Itokawa, where production rates are highest. If, in fact, the grains spent much of their time in deeper locations, then the appropriate production rates are lower, the ages older, and the erosion rate slower. Other possible interpretations call on other means to resurface the sampling sites of Hayabusa: gravitational shaking in an asteroid or planet flyby, or a single large impact rather than many tiny ones. That large impact might even be the one that ejected Itokawa from a larger, parent asteroid. Meier et al. (2014) speculate that the two LL chondrites known to have matching, 1.5 Ma exposure ages (Appley Bridge and Chelyabinsk) might derive from the same event that created Itokawa.

REFERENCES

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