***IN-SITU* RADIOMETRIC AGE DETERMINATION: A CRITICAL COMPONENT OF MARS EXPLORATION.** J. B. Plescia[1] and T. D. Swindle[2], [1]Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, MD 20723, jeffrey.plescia@jhuapl.edu. [2]Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, tswindle@lpl.arizona.edu.

Introduction: In order to understand the geologic, climatic and possibly the biologic evolution of Mars, the absolute timing of events must be established. Questions of climate change, glacial processes, availability of surface water, recent volcanism, and atmospheric evolution all hinge on determining when those events occurred in absolute time. Resolving the absolute timing of events has become even more critical with the suggestions of currently active glacial and perhaps fluvial activity and very young volcanic activity.

Background: To date, only the relative chronology of events has been firmly established [1]. This has been accomplished through the use of impact crater counts in which the frequency of impact craters per unit area greater than or equal to some diameter is used as a reference for comparison among surfaces; the higher the frequency, the older the age [2-3]. This technique allows surfaces and events on different parts of a planet to be correlated in time. But, the technique provides only the relative age (e.g., surface A is older than surface B or Surface C is the same age as Surface A). For the absolute age of a surface / event to be determined, either the various units of interest must be radiometrically dated (as might be done on the Earth) or a calibration of the cratering rate must be established such that the frequency of impact craters can be used to estimate the absolute age (as has been done on the Moon).

Lunar Chronology: The returned Apollo and Luna samples have allowed an estimate to be made of the absolute impact cratering rate on the Moon, thus providing a calibration between the frequency of impact craters on a surface and absolute age [4-11]. Figure 1 shows a calibration curve for the Moon. Using such a calibration, once the impact crater frequency is measured for a surface, its absolute age can be approximately determined.

It should be noted however, that significant uncertainties still remain with respect to the lunar impact cratering rate, at both young and old ages. At the young end, the ages associated with Copernicus and Tycho are inferential - based on samples suggested to be associated with the formation of those craters from the Apollo 12 and 17 sites (respectively). If those assumptions are not correct, the decay rate between ~3 Ga and 53-25 Ma (North Ray and Cone Crater dates) could be different from what is illustrated. At the old end, it has been suggested that a spike in the cratering rate occurred around 3.9 Ga – the so called Late Heavy Bombardment [12-18], although this remains a controversial topic. It has also been suggested that the cratering rate over the last several billion years has not been uniform, but rather has been punctuated by periodic spikes in the rate [19-20].

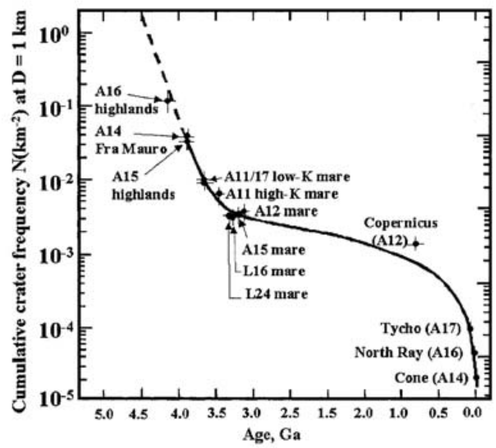

Figure 1. Lunar cratering rate based on observed crater frequencies and radiometrically determined ages from returned samples. Figure adapted from [12].

Mars Chronology: Several investigators have suggested correlations between the lunar cratering rate and the cratering rate for Mars, thus attempting to establish a calibration for the cratering rate at Mars [21-26]. These estimates are based on the lunar chronology which is then extrapolated to Mars with corrections for velocity, gravity, projectile sources, and atmospheric shielding [27-30]. The result is that any uncertainty in the lunar crater rate is carried forward and then amplified by the uncertainties specific to Mars.

The Problem: Despite such attempts at estimating the impact cratering flux at Mars, there remains considerable uncertainty and debate. For example, using the frequency of impact craters $\geq$1 km in diameter, there can be large uncertainties in the absolute age between different models. Figure 2 shows two model fluxes. There is good agreement for the older period of time – the Noachian (>3.8 Ga). However, at younger ages, a given crater frequency indicates very different absolute ages depending upon the model. For example, the solid red line denotes a crater frequency of 0.001 craters $\geq$1 km / km^2 (1000 / 10^6 km^2) – the models indicate absolute ages of 2.1 to 1.4 Ga. Such uncertainties are far from satisfactory when the details of planetary evolution are being studied. These uncertainties aside, one must still make the assumption that one of the models is, in fact, correct.

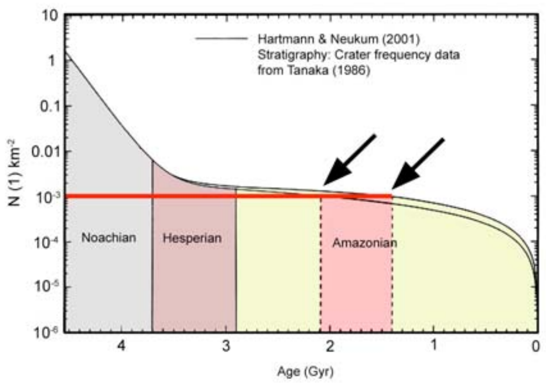

Figure 2. Comparison of different proposed absolute chronologies. The two arrows show the points of intersection of a single crater frequency (red line) for the two models. Area shaded in pink indicates the range of age between two model. Figure adapted from [26].

Additional uncertainties arise when the statistics for different crater diameters are considered. For example, the Cerberus Plains in southern Elysium is a well-defined volcanic surface and is, in fact, the youngest large-scale volcanic surface on Mars [31-34]. When the 2 km crater number is used (23 ± 8) [35] an absolute age of 143 ± 40 Ma is obtained using the chronology of [36]. This absolute age is similar to the absolute ages of some of the martian meteorites [37-38] whose petrologic characteristics suggest that they may have been derived from this unit. More recently, however, Hartmann and others [39-40] have argued for very much younger ages for this same surface. Using craters in the 100s meter diameter range, they have suggested the Cerberus surfaces could be as young as ~9 Ma. At face value the two methods do not agree, indicating either that one of the two crater-based ages is incorrect or that the suggested geologic history of the site is incorrect. The frequencies of impact craters in the 100s meter diameter range have also been used as a basis to suggest very young glacial, fluvial, and volcanic events elsewhere on Mars [41-43].

The Solution: To calibrate the martian chronology, a radiometrically datable sample from a well-defined stratigraphic surface must be analyzed. That surface must be expansive enough such that it has a sufficient number of impact craters to allow the calculation of crater frequencies; it must also be young enough such that it has not reached cratering equilibrium. The surface must also be small enough that it represents a single geologic event and it should have suffered minimal post-emplacement alteration, such as fluvial erosion or weathering. For immediate practical purposes, this limits consideration to volcanic surfaces such as those found in the Tharsis and Elysium regions.

Programmatic Context: Mars sample return missions have been studied for decades. Despite a variety of different implementation approaches, the cost has always been high and the probability of success low (because of the multiple steps required to reach and land on Mars, collect the sample, and return it to Earth). Within the current budgetary framework, the potential for a single (let alone multiple) sample return missions is very low. In addition, with a programmatic focus on life, it is unlikely that a sample return mission would be sent to a geologially simple (in the minds of some, boring) site. This context makes *in situ* age determination experiments all the more critical to unraveling the absolute timing of events on Mars.

Discussion: For initial *in situ* dating attempts, a volcanic surface composed of well-defined lava flows would be appropriate. While datable material might be found in a sedimentary or polar section, at present a site could not be selected with any confidence and such a date, while providing a local absolute age, would probably not constrain the cratering rate. Similarly, while datable material can be found at the Viking, Pathfinder, and Spirit landing sites, those materials are not in-place and thus would not provide a constraint on the cratering rate (they would provide age data similar to the martian meteorites).

To constrain the impact cratering rate, multiple sites having different impact crater frequencies will need to be analyzed. Young and old sites each have advantages and disadvantages. For example, the Lower Amazonian Cerberus site is young and relatively pristine, hence the samples would be expected to be unaltered. But, because it is young it has few impact craters. On a crater frequency / absolute age plot (e.g., Figures 1 and 2) the data point would be near the origin (in the lower right) and with the associated uncertainties in both the age and the crater frequency, it would place only broad constraints on the impact cratering rate. However, in the case of Cerberus, it would establish whether that surface is hundreds of millions of years old (and consistent with the ages of some martian meteorites) or only millions of years old.

An older site, the Hesperian-aged Lunae Planum, would provide a data point for a surface whose crater frequency would be better constrained and whose absolute age would have smaller relative uncertainties. Lying farther from the origin it would provide tighter constraints on the cratering rate. However, an older site would be subjected to more surficial weathering processes that might have altered the sample and thus complicate the age determination.

Several different analytic schemes could be employed on the surface of Mars. Each has its limitations and different state of technological readiness as well as differences in sample requirements. [44] reviewed a number of methods that might be employed, including K/Ar, U/Th-He, Rb/Sr and cosmogenic nuclides (e.g., ^{3}He, ^{21}Ne, ^{36,38}Ar, ^{10}Be, ^{14}C, ^{26}Al and ^{53}Mn). Dating the material with cosmogenic nuclides might also be used to provide information about local events such as surface mantling. Other methods such as the U and Th decay series are possible, but the technology is undeveloped.

The instrumentation for two of these techniques are fairly well developed and have been matured to a relatively high TRL. These include a combination of K/Ar and cosmogenic noble gases [45] and Rb/Sr [46-48]. Only a small samples needs to be acquired for analysis; the minimum sample size is driven more by the need to manipulate it than for analysis. Using a small rock coring drill, a sample could be collected from below the immediate surface (to avoid any surficial weathering processes) and placed in the instrumentation for processing and analysis. Sample acquisition and processing technologies have been extensively developed for the Phoenix and MSL missions. In 2002 a Mars Scout proposal was submitted in which it was proposed to conduct *in situ* age determination using the K/Ar technique.

For a given site, multiple samples should be analyzed to ensure that a reliable age is established. Ideally, the ages would all be identical within the analytic uncertainty as they would reflect a single geologic event - for a volcanic surface the time of eruption of the lava.

Conclusions: At issue here is not whether any individual cratering rate model is better than another, the issue is that the problem is so poorly constrained that it will never be resolved without analysis of appropriate samples. *In situ* radiometric age determination of materials on Mars is critical to establishing the absolute timing of events. The precision which could be obtained (15-50%, depending upon the technique) would not approach that routinely obtained for laboratory measurements, but it would be far better than the uncertainties that currently exist for locations such as Cerberus and the larger disagreements in the absolute age of older surfaces. Without understanding the absolute timing, the geologic and climatic history and the potential for biologic processes can not be understood with any certainty.

References: [1] Tanaka K. L. (1986) *Proc. 17th LPSC, JGR, 91*, Supplement, 139-158. [2] Baldwin R. B. (1949) **The Face of the Moon**. [3] Wilhelms D. E. (1987) **The Geologic History of the Moon.** *USGS Prof. Paper 1348*. [4] Hartmann W. K. (1972) *Astrophys. Space Sci., 17*, 48-64. [5] Soderblom L. A. and Lebofsky L. (1972) *JGR, 77*, 279-296. [6] Neukum G. *et al.* (1975) *Proc. 6th LSC*, 2597-2620. [7] Neukum G. and König B. (1976) *Proc. 7th LSC*, 2867-2881. [8] Hartmann W. K. *et al.* (1981) **Basaltic Volcanism on the Terrestrial Planets**, 1049-1128. [9] Neukum G. and Ivanov B. (1996) in **Hazards Due to Comets and Asteroids**, 359-416. [10] Stöffler D. and Ryder G. (2001) *Space Science Rev., 96*, 9-54. [11] Hartmann W. K. *et al.* (2007) *Icarus, 186*, 11-23. [12] Ryder G. (2002) *JGR, 107*, E4, 10.1029/2001JE001583. [13] Tera F. *et al*. (1974) *EPSL, 22*, 1-22. [14] Kring D. A., and Cohen B. A. (2002) *JGR, 107*, E2, 10.1029/2001JE001529. [15] Gomes R. *et al.* (2005) *Nature, 435*, 466-469. [16] Strom R. G. *et al.* (2005) *Science, 309*, 1847-1850. [17] Bottke W. F. *et al.* (2007) *Icarus, in press*. [18] Chapman C. R. *et al.* (2007) *Icarus, in press.* [19] Farley K. A. *et al.* (2006) *Nature, 439*, 295-297. [20] Culler T. S. *et al.* (2000) *Science, 287*, 1785-1788. [21] Neukum G. and Wise D. U. (1976) *Science, 194*, 1381-1387. [22] Hartmann W. K. (1977) Icarus, 31, 260-276. [23] Soderblom L. A. (1977) *in* **Impact and Explosion Cratering**, 629-633. [24] Neukum G. and Hiller K. (1985) *JGR, 86*, 3097-3121. [25] Neukum G. and Ivanov B. A. (1994) *in* **Hazards Due to Comets and Asteroids**, 359-416. [26] Hartmann W. K. and Neukum G. (2001) *Space Sci. Rev., 96*, 165-194. [27] Wetherill G. W. (1989) *Meteoritics, 24*, 15-22. [28] Steel D. (1998) *Planet. Space. Sci., 46*, 473-478. [29] Levison H. F. *et al.* (2000) *Icarus, 143*, 415-420. [30] Ivanov B. (2001) *Space Sci. Rev., 96*, 87-104. [31] Plescia, J. B. (1990) *Icarus, 88*, 465-490. [32] Plescia J. B. (2003) *Icarus, 164*, 79-95. [33] Burr D. M. *et al.* (2002) *GRL, 29*, 1, 1013, doi:10.1029/2001GL013345. [34] Keszthelyi L. *et al.* (2006) *J. Geol. Soc. London, 163*, 253-264. [35] Plescia J. B. (1999) *LPS XXX*, Abstract 1627. [36] Tanaka K. L. *et al*. (1992) *in* **Mars**, 345-382. [37] Nyquist L. E. *et al*. (2006) *LPS XXXVII*, Abstract 1723. [38] Nyquist L. E. *et al.* (2001) *Space Sci. Rev., 96*, 105-164. [39] Hartmann W. K. (2005) *Icarus, 174*, 294-320. [40] Berman D. C. and Hartmann W. K. (2001) *Icarus, 159*, 1-17. [41] Neukum G. *et al*. (2007) *LPS XXXVIII*, Abstract 2271. [42] Head J. W. *et al*. (2005) *Nature, 434*, 346-351. [43] Neukum G. *et al.* (2004) *Nature, 432*, 971-979. [44] Doran P. T. *et al.* (2004) *Earth Science Rev., 67*, 313-337. [45] Swindle T. *et al.* (2003) *LPS XXXIV*, Abstract 1488. [46] Anderson F. S. *et al.* (2007) *LPS XXXVIII*, Abstract 2153. [47] Cardell G. *et al.* (2002) *LPS XXXIII*, Abstract 2407. [48] Stewart B. *et al.* (2001) *11th Ann. Goldschmidt Conf.*, Abstract 3891.