PLANETARY GEOCHRONOLOGY: WHAT CAN BE DONE IN SITU, AND WHAT NEEDS SAMPLE RETURN? B. A. Cohen, NASA Marshall Space Flight Center, VP62, 320 Sparkman Dr., Huntsville AL 35805 (Barbara.A.Cohen@nasa.gov).

Introduction: Geochronology is a fundamental component of planetary sample analysis, proving timing of major events recorded in rocks and thus context for the conditions prevailing on the planet at the time of the event. In terrestrial laboratories, the absolute age of events can be measured to ±1 Myr or better. But an age is more than just an isotopic ratio - it is an interpretation of that number, tying it to the petrogenesis of the rock. Geochronologists have largely shied away from in situ dating because its sensitivity is going to be much less than we are used to in the laboratory and the detailed understanding of the rock's petrogenesis can be difficult to achieve. However, appropriate application of in situ dating can overcome such objections in specific situations and become a fundamental capability for robotic probes.

The geochronology instrument must be integrated into a suite of other instruments and measurements to give the rock context. Commonly-used and highly-appropriate measurements include remote sensing for geologic setting, imaging and microscopic imaging for petrology, and microanalytical techniques for chemical and mineralogic composition and variation. These measurements must be made with as much contextual information about the sample's location, composition, and properties as possible to ensure that the fundamental dating assumptions are valid, namely that the samples forming the isochron are cogenetic and that the system is closed, and to enable a correct interpretation of the geologic event reflected in the radiometric age. Furthermore, in situ geochronology must generate an age that enables a geologic interpretation that clearly improves upon current knowledge. Many problems in geochronology require the resolution and sensitivity of a terrestrial laboratory and therefore cannot be solved by in situ instrumentation. However, several fundamentally important objectives on the Moon, Mars, and other rocky bodies could be met with this approach. Here we discuss three specific applications.

Flux of lunar volcanism: The relationship between basalt composition, location and age is crucial in understanding the nature of lunar magmatism. In the absence of sample return, our only way of understanding the ages of these rocks is via crater-counting techniques on orbital images. Recent missions have enabled discovery of basaltic units with crater-count ages as young as 1.2 Ga, including those in Oceanus Procellarum, the Aristarchus Plateau and Mare Moscoviense on the lunar far side [1, 2]. These young basalts are unknown in the returned sample collection but may be a clue to the origin of some lunar basaltic meteorites such as Kalahari 009 and NEA 003 [3]. Obtaining the age and composition of a young basalt flow and tying this information to the crater count and composition is therefore a desirable measurement [4, 5]. The age must have an uncertainty smaller than the derived model age from crater counting, which depends both on the uncertainty in the flux curve and in the crater counting itself. The uncertainties associated with these ages vary depending on the exact flow unit, but range from 0.05 to >0.7 Ga, with the mean uncertainty around 200-300 Ma. Therefore, obtaining an age within 100 Ma of a young or far side basalt will help distinguish between models where the lunar heat engine shuts down early or late and resolving whether progressively younger basalts have systematic compositional variations related to an evolving source region [6, 7]. However, in situ ages will not be able to provide source-region isotopic characteristics or detailed trace-element contents, both of which are crucial measurements [5]. Furthermore, there will not be enough in situ opportunities to sample the full range of compositions, and we will continue to rely on chance delivery of such lithologies to us as small clasts in lunar meteorites or as pieces tossed to sampled locations.

Lunar craters and basins: The lunar crater record provides the baseline with which we calibrate the absolute ages of all cratered surfaces in the inner solar system. While the lunar crater curve is well-bounded between ~1 and ~4 Ga, the curve on the older and younger ends is poorly constrained. Several high-priority activities for lunar science are tasks that help define this curve at its extremities.

The most important candidate on the Moon for absolute dating is the South Pole-Aitken (SPA) basin. It is the largest, deepest, and stratigraphically oldest impact basin on any terrestrial planet. Though collecting impact-melt rocks in situ from nearside basins such as Imbrium is impossible because of their mare basalt fill, the SPA basin appears not to be covered with basalt, but instead retains the signature of its impact melt sheet in remote sensing data [8]. The oldest age within the samples might be expected to correspond to the SPA basin age, for which an age uncertainty of ±100 Ma would be sufficient and could be achieved in situ. However, dating of younger basins within SPA such as Apollo and Ingenii would bound SPA and elucidate the subsequent impact history of the far side. Distinguishing between SPA melt itself and reworked material from these younger basins requires detailed trace-element analysis and geochronology by multiple techniques with laboratory precision [9].

The exact ages of young craters such as Copernicus provide important calibration points for the lunar chronology at young ages. Crater counts on the Copernicus ejecta blanket indicate an age of 1.5 Ga, but Apollo 12 samples collected on one of the rays of Copernicus crater have a significantly younger age of 800-850 Ma – in fact, virtually all Apollo 12 samples have a 600-900 Ma overprint [10, 11]. This could mean that we did not collect material from Copernicus or that the samples do not represent the surface material dated with crater counts. Dating material from within young craters to uncertainties of ±100 Ma, which may within reach of an in situ instrument, would significantly enhance the lunar calibration curve.

Another important science objective is to determine whether there was a lunar cataclysm, defined as the creation of several nearside basins (Imbrium, Serenitatis, Nectaris, Crisium, Orientale) within a short period (200-20 Myr) [12, 13]. Because the cataclysm is defined by multiple events closely-spaced in time, the uncertainty in age required is better than 0.02 Ga (20 Ma), along with detailed trace-element (ppb) analyses, to distinguish among samples from distinct impacts during this time. This level of precision is probably not achievable with in situ analyses, so this is a science question that may not be answerable except in terrestrial laboratories.

Martian history: The absolute ages of Mars's geological events, and thus the time history of the planet's evolution, will not be fully understood until the relative Martian chronology derived from stratigraphy is tied to an absolute chronology via radiometric dating of Martian rocks. Absolute ages of Martian surface units are uncertain by as much as a factor of two on older surfaces and disagreements can be an order of magnitude or more on younger, lightly-cratered surfaces [14, 15]. In situ age dating with an uncertainty of ±100 Ma would be a significant improvement, especially for sites in middle Mars history (late Hesperian through mid-Amazonian). Site(s) dated in situ would better constrain the Martian crater production curve, thereby improving estimates of the absolute ages of Mars's other geological units.

As with all samples, the rocks selected for in situ dating must be geologically well characterized to ensure our understanding of the provenance and geological history of the dated sample, and petrologically well-characterized to ensure understanding of the geochronologic results. And again, additional information on the source-region isotopic characteristics and detailed trace-element contents, only currently achieveable by laboratory analyses, are crucial to understanding Mars' magmatic history.

Some of the foremost objectives for understanding Mars have to do with fluids on the surface, with both geologic and astrobiologic implications. The geochronology of alteration minerals provides a context for the timing and duration of surface fluids and surface conditions. Such geochronology relies on careful separation of the altered phases, which are volumetrically small, from the host rock [16, 17]. Separation may be mechanical or by placement of small beams, but either way, requires dexterous manipulation and characterization of both the altered phases and the host lithology on scales that are not currently achievable with in situ analysis. Therefore, sample return is required to address this scientific issue.

Other bodies: Our knowledge of the absolute surface age on other bodies, such as Mercury, asteroids, and the outer planet satellites, relies wholly on the crater calibration record for the Moon. The factors that cause the crater flux to change in different areas of the solar system are complex, so providing even a rough absolute age for these bodies would go a long way toward calibrating the crater curve, enabling us to understand the surface history of the body itself as well as how the dynamic flux varied in different parts of the solar system throughout time. On the one hand, in situ techniques may be the only way to address geochronology, as sample return may be prohibitively expensive and samples do not arrive naturally to the Earth (except asteroids). On the other hand, significant challenges remain to in situ geochronology techniques on these bodies, including predicting the concentration of radiogenic elements, understanding appropriate characterization and handling techniques, and mission constraints for operation in extreme environments. Upcoming missions (MESSENGER, Dawn, Jupiter/Europa flagship) may help inform design of appropriate geochronology instruments for future missions.

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