GEOCHRONOLOGY AS A FRAMEWORK FOR PLANETARY HISTORY THROUGH 2050. B. A. Cohen[1], R. Arevalo Jr.[2], W. F. Bottke, Jr.[3], P. G. Conrad[2], K. A. Farley[4], C. I. Fassett[1], B. L. Jolliff[5], S. J. Lawrence[6], P. R. Mahaffy[2], C. Malespin[2], T. D. Swindle[7], M. Wadhwa[8], [1]NASA MSFC (Barbara.A.Cohen@nasa.gov), [2]NASA GSFC, [3]Southwest Research Institute, [4]California Institute of Technology, [5]Washington University, [6]NASA JSC, [7]University of Arizona, [8]Arizona State University.

Introduction: In the decades of planetary exploration since the 1970's, the science community has made great progress characterizing the contemporary state and relative geologic histories of the terrestrial and outer planets, satellites, and primitive bodies. In parallel, we have significantly advanced the state-of-the-art in laboratory-based absolute geochronology techniques and exposure age determinations applied to planetary samples. Despite this progress, little headway has been made improving our knowledge of absolute ages for common events, such as the Late Heavy Bombardment, planetary volcanism, and the establishment of astrobiologically-relevant environments. In the next 40 years, we advocate constructing a common framework of geologic time across our solar system, linking individual planetary evolution to solar system history. Accomplishing this theme requires the integration of geochronology with in situ investigations, targeted sample return missions, and continued advancements in laboratory analysis and modeling.

Absolute Geochronology: Our knowledge of absolute surface ages on other bodies, including Mars, Mercury, asteroids, and outer planet satellites, relies primarily on the crater calibration record for the Moon. While lunar cratering history is bounded between ~1 and ~4 Ga by isotopic ages of the Copernicus and Imbrium impacts and multiple volcanic units, the impact rates before 4 Ga and after 1 Ga are more poorly constrained [1]. Absolute ages of Martian surface units can be uncertain by a factor of two on older (Hesperian) surfaces, and by an order of magnitude on younger, lightly-cratered surfaces [2, 3]. This uncertainty encompasses major events on the terrestrial planets, including thermal evolution, impact bombardment, and climate change.

Planetary Origin: Chemical evolution of planetary bodies, ranging from asteroids to the large rocky planets, is thought to begin with differentiation through solidification of magma oceans. Rocks from the crust and mantle date the processes of silicate (and metal) segregation of planetary formation and magmatic evolution – yet ancient lunar crustal rocks have ages that range to much younger than magma-ocean models would predict [4, 5]. The most ancient Martian meteorite, ALH84001, crystallized much later than predictions of crustal formation on Mars [6]. Some worlds, such as Europa and Venus, have evidence of extremely recent activity, indicating long-lived heat sources driving crustal processes. Identifying the most ancient crust across the solar system and obtaining more precise ages of the oldest and youngest magmatic products will provide a way to understand the dynamics of magma oceans and crust formation, and the longevity and evolution of interior heat engines and distinct mantle/crustal source regions.

Bombardment History: Determining the flux of impactors on all bodies, and whether it was constant across the inner and outer solar system, is a primary goal of the planetary science community. The energetic nature of impact cratering can have wide-ranging consequences extending to a planet's subsurface and atmosphere, perhaps destroying life or creating transient abodes for it. One of the biggest questions is whether there was a lunar cataclysm, or late heavy bombardment, defined as the creation of multiple lunar nearside basins within a short period [7, 8]. This event potentially relates the impact bombardment history of the inner solar system to the time when life began on Earth [9]. Yet, the crater-based age estimates of the Rheasilvia basin on Vesta range from 1 Ga to 3.5 Ga [10, 11] and the epoch of large-basin formation on Mercury and Mars is uncertain by hundreds of Myr [12]. It is crucial to determine the time interval for the creation of large basins on the terrestrial planets and establish how the flux delivered to inner and outer planets reflects the dynamical evolution of the solar system [13].

Astrobiology: An incomplete knowledge of absolute Martian geochronology limits our understanding of the timing of the planet's evolutionary milestones – for example, whether the Noachian-Hesperian boundary occurred before, after or concurrent with the late heavy bombardment on the Moon [2], or when Mars' surface environment transitioned from wetter and more chemically neutral conditions to volcanically dominated, acidic, oxidizing, and dry surface conditions [14]. Absolute dating also will be required to relate habitability markers to the timescale of evolution of life on Earth [15]. Moreover, measurements of exposure ages are proxies of biosignature preservation potential, enabling the prioritization of samples to be returned to Earth and/or analyzed by life-detecting techniques in situ.

Strategies through 2050: Through the next several decades, a sustained effort will be required to create a framework that relates planetary geologic events to each other. In this decade, investment is needed to increase the technology readiness levels to TRL 6 for in situ geochronology instruments using complementary radiogenic isotopic systems. Sample collection and handling systems are required to ingest samples for all in situ dating methods; these systems need to be matured, along with operating scenario for their use, such that the operational burden for sample collection and analysis is reduced. Further improvements to spacecraft mobility and dexterity will enable more geologic units to be interrogated during each mission. In the 2020's, these technologies will be ready to be included in developing missions to key stratigraphic targets on terrestrial planets, alongside planning sample-return efforts for the Moon and Mars. In the 2030's, an in situ geochronology component should be considered as an augmentation to human exploration of the Moon and Mars and for robotic missions to targets beyond our current capabilities for sample return in the inner and outer solar system (including Mercury, Venus, Europa, and Io). By the 2040's, we should expect in situ geochronology to be a standard capability on planetary landers. In parallel with these developments, Earth-based laboratory capabilities for returned samples must continue to advance in sensitivity, accuracy and precision, as well as efficiency in the handling and processing of diverse samples.

In situ Dating: The capability of flight instruments to conduct in situ geochronology is specified in the NASA Planetary Science Decadal Survey and the NASA Technology Roadmap [16, 17] as needing development to serve the community's needs. Radiometric dating on Mars is now a validated technique, although the Curiosity method is not purpose-built for dating and requires many assumptions that degrade its precision [18]. To achieve more precise and meaningful ages, multiple groups are developing dedicated in situ dating instruments [19-23]. These instruments are on track to demonstrate TRL 6 readiness by 2020 and will need to be selected in the 2020's and 2030's for competed and directed flight missions to relevant destinations where in situ precision (±100 Myr) can provide meaningful constraints on geologic history.

Sample Return: High-precision geochronological investigations of samples returned from selected locations on the Moon, including the New Frontiers target South Pole-Aitken Basin, would significantly advance our understanding of lunar chronology and solar-system processes. Such investigations will allow us to distinguish events closely spaced in time, and better evaluate samples having complex chronologic histories. In particular, both the old and young ends of the crater flux curve and lunar magmatic history require additional constraints [24, 25]. Though Mars sample return (MSR) efforts are driven by the search for astrobiologically relevant materials, a crucial objective for MSR is to establish an absolute geochronological anchor for the impact history of Mars. Samples suitable for these efforts [26, 27] are not always considered high-priority in landing site and architecture discussions. We urge the community to make a geochronology anchor sample a critical sample in MSR, or to consider groundbreaking MSR to a suitable surface for this purpose. Such a sample would be able to be studied using multiple geochronological systems in state-of-the-art laboratories on Earth, as well as other techniques (such as isotopic and trace element analysis) that provide additional constraints on understanding the history of the planet.

Laboratory Facilities: Missions such as Genesis and Stardust drove the advancement of laboratory capabilities for the analysis of smaller and smaller samples [28] and the streamlining of analytical protocols (e.g., beginning with non-destructive techniques). For sample geochronology, the primary instruments are high precision mass spectrometers, equipped with thermal or plasma ionization sources, secondary ion and noble gas mass spectrometers, and accelerator mass spectrometers. Sustained investment in laboratory upgrades and advancements, as well as in training future generations of research analysts, will be needed to extract maximum scientific return from geochronological investigations of existing and future samples from planetary targets.

References: [1] Stöffler (2001) *Space Sci Rev* 96, 9-54. [2] Doran (2004) *Earth Sci Rev* 67, 313–337. [3] Tanaka (1986) *J Geophys Res* 91, 139. [4] Borg (2015) *Met Planet Sci* 50, 715-732. [5] Borg (2011) *Nature* 477, 70-72. [6] Lapen (2010) *Science* 328, 347-351. [7] Ryder (1990) *EOS* 71, 313, 322-323. [8] Tera (1974) *Earth Planet Sci Lett* 22, 1-21. [9] Kring (2001) *J Geophys Res* 107, 10.1029/2001JE001529. [10] Schmedemann (2014) *Planet Space Sci* 103, 104-130. [11] O'Brien (2014) *Planet Space Sci* 103, 131-142. [12] Werner (2014) *Earth Planet Sci Lett* 400, 54-65. [13] Bottke (2011) https://sservi.nasa.gov/wp-content/uploads/drupal/WilliamFBottke-lunarbombardment.pdf. [14] Bibring (2005) *Science* 307, 1576-1581. [15] Conrad (2011) mepag.nasa.gov/reports/decadal/PamelaGConrad.pdf. [16] National Research Council (2011) *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. [17] Barney (2012) http://www.nasa.gov/sites/default/files/501624main_TA08-ID_rev5_NRC_wTASR.pdf. [18] Farley (2014) *Science* 343. [19] Farley (2013) *Geochim Cosmochim Acta* 110, 1-12. [20] Cohen (2014) *Geost Geoanal Res* 38, 421-439. [21] Anderson (2015) *Rapic Comm Mass Spect* 29, 191-204. [22] Cho (2016) *Planet Space Sci* 128, 14-29. [23] Devismes (2016) *Geost Geoanal Res*. DOI: 10.1111/ggr.12118. [24] Treiman (2011) http://www.lpi.usra.edu/decadal/leag/AllanTreimanMoon.pdf [25] Ryder (1989) *Eos* 70, 1495-1509. [26] MEPAG Next Decade Science Analysis Group (2008) *Astrobiology* 8, 489-535. [27] iMARS Working Group (2008) http://mepagjplnasagov/reports/indexhtml. [28] Davis (2011) http://www.lpi.usra.edu/decadal/captem/curation Instrumentation.doc.