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The Inner Solar System Chronology (ISOCHRON) Lunar Sample Return Mission Concept: Revealing Two Billion Years of History

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Abstract

We present the Inner SOlar System CHRONology (ISOCHRON) concept to return samples of the youngest extensive mare basalt for age-dating and geochemical analysis. The young basalt is exposed at a site southwest of Aristarchus Plateau, for which complete remote-sensing data are available for thorough landing site analysis. Data from these samples would revolutionize the ability to assign exposure ages to rocky planetary surfaces based on the samples returned by Apollo and Luna. Their petrology and geochemistry will enable assessment of the most recent voluminous lunar magmatism. Regolith evolution and mixing models such as ballistic sedimentation would be directly testable to provide crucial ground truth that would enhance the science value of current and future remotely sensed data sets. ISOCHRON's science goals support NASA's Artemis program to return to the Moon and its related robotic programs currently in planning.

Unified Astronomy Thesaurus concepts: Lunar geochronology (954); Lunar petrology (967); Lunar craters (949); Planetary science (1255); Planetary probes (1252)

1. Introduction

The Moon is the "Rosetta Stone" for understanding the formation and evolution of the inner solar system. As the primary body beyond Earth for which we have obtained samples from known geological context, the Moon provides the foundation for many models of solar system bombardment, planetary thermal and volcanic differentiation, and regolith evolution. The Moon also preserves many of the primary lithologic and geochemical products of its original differentiation, the equivalents of which have largely been lost on Earth. Despite this strong foundation, critical gaps remain that hinder our ability to interpret the history of all inner solar system bodies. A critically important obstacle is that neither the Apollo nor Luna programs returned volcanic samples that formed within the past 3 billion yr (Ga), yet orbital imaging and crater size–frequency distribution (CSFD) measurements demonstrate that there may be extensive volcanic surfaces as young as 1 Ga, and perhaps younger, on the Moon. Testing these derived ages and understanding how the Moon produced such young volcanic rocks is one of NASA's highest solar system exploration priorities.

To address these and other issues described herein, we formulated the Inner SOlar System CHRONology (ISOCHRON) lunar sample return mission concept. Laboratory analysis of samples returned by ISOCHRON would (1) resolve the post–3 Ga impact history of the inner solar system, (2) determine the late-stage thermal and magmatic history of the Moon, and (3) shed critical light on lunar regolith maturation and mixing processes. ISOCHRON would advance these goals by landing on a young, nearside lunar lava flow and collecting basalt and regolith for return to Earth. These samples would then be subjected to the full range of analysis in terrestrial laboratories to measure their radiometric/exposure ages, geochemistry, mineralogy, spectral properties, and space weathering products.

The measured ages, when related to the size–frequency distribution of impact craters at the site, would provide a new calibration point from the basalt unit for the CSFD-based chronology models upon which a large portion of our understanding of the history of the inner (and, to a substantial extent, the outer) solar system depends. The compositional data on the young lava would reveal how the Moon's interior and, by extension, those of the other terrestrial planets have evolved through time. Spectral measurements would provide crucial ground truth for remotely sensed data sets from the Moon and other terrestrial planets. Analyses of regolith would determine the extent of lateral and vertical mixing, space weathering, and exposure ages of lunar soils, which in turn form the basis for understanding regolith on all airless bodies. All of these science goals have direct traceability to goals contained in the current decadal survey for planetary science (National Research Council 2011, hereafter PSDS2013 report; see Section 2.4), as well as numerous planetary community assessments (National Research Council 2007, hereafter SCEM; Lunar Exploration Analysis Group (LEAG) 2017a, 2017b).

2. Background, Goals, and Objectives

It is impossible to overstate the value of returned planetary samples. The returned Apollo and Luna samples gave rise to the field of planetary geology and shed light on the earliest epoch of Earth–Moon system history. Lunar sample research, coupled with the global context provided by orbital measurements over the succeeding decades, is the basis for understanding the bombardment history of the Moon and inner solar system, the early thermal evolution of planets and differentiated planetesimals, and the physical and chemical effects of exposure to the space environment. Although the Apollo and Luna missions accomplished fundamental science objectives, with the hindsight of subsequent lunar mission data, particularly from the Lunar Prospector, Clementine, and Lunar Reconnaissance Orbiter (LRO), we now understand that the sites visited by Apollo and Luna represented a highly biased sampling of lunar history. All of the rocks in the existing sample collections originally crystallized over 2.8 billion yr ago. Furthermore, all landing sites happen to be clustered within a relatively small and geochemically anomalous region on the Moon's nearside, which is termed the Procellarum KREEP Terrane, signifying the signature of a geochemically enriched reservoir typified by elevated contents of K, the rare-earth elements, and P, among others (e.g., Jolliff et al. 2000).

The 2003 Planetary Science Decadal Survey, the SCEM report, and the PSDS2013 report (see Section 2.4) concluded that landed lunar missions are critical for understanding fundamental solar system processes and revealing solar system history. These and other community assessments (e.g., Lunar Exploration Analysis Group 2017a, 2017b) have also consistently called for sample return missions from two particularly important terrains: (1) the ancient (>4 Ga old) lunar basins (e.g., South Pole-Aitken, Nectaris) and (2) the youngest (<2 Ga old) lunar basalts. Sampling these terrains is key to fully defining the lunar stratigraphic timescale, the history of basin-forming events, and the thermal and magmatic evolution of the lunar interior.

ISOCHRON focuses on the youngest lunar flood basalts and is designed to collect the first igneous lunar samples from the latter two-thirds of solar system history. Analysis of these samples would enable the following goals: (1) determine the timing of impact events that occurred in the middle of inner solar system history, (2) determine the late-stage thermal and magmatic history of the Moon, and (3) test hypotheses for regolith mixing processes and establish critical ground truth for remote-sensing data. These goals are detailed in the following subsections.

2.1. Goal 1: Determine the Timing of Events that Occurred in the Middle Half of Inner Solar System History

The Moon is the "witness plate" for the bombardment of the inner solar system, providing a record of lunar geologic history that is the foundation of understanding the relative histories of other rocky planets, including Earth. Measurements using CSFD allow the determination of relative ages for different geological units across a rocky body; older surfaces exhibit more and larger craters, whereas younger surfaces have fewer, smaller craters. Relative ages can be related as the cumulative number of craters having diameters ⩾a reference value, e.g., 1 km, denoted $N_{\mathrm{cum}}(D \geqslant 1)\,\mathrm{km}^{-2}$ or $N(1)$ (Hartmann 1966; Crater Analysis Techniques Working Group 1979; Neukum 1983; Hiesinger et al. 2000). The early 1980s saw the development of a lunar cratering chronology to allow the determination of absolute ages from $N(1)$ values for unsampled geological units across the Moon (e.g., Neukum 1983; Neukum et al. 2001). The chronology is based on connecting lunar sample ages with $N(1)$ values measured for the sampled geological units at the Apollo and Luna landing sites (Figure 1).

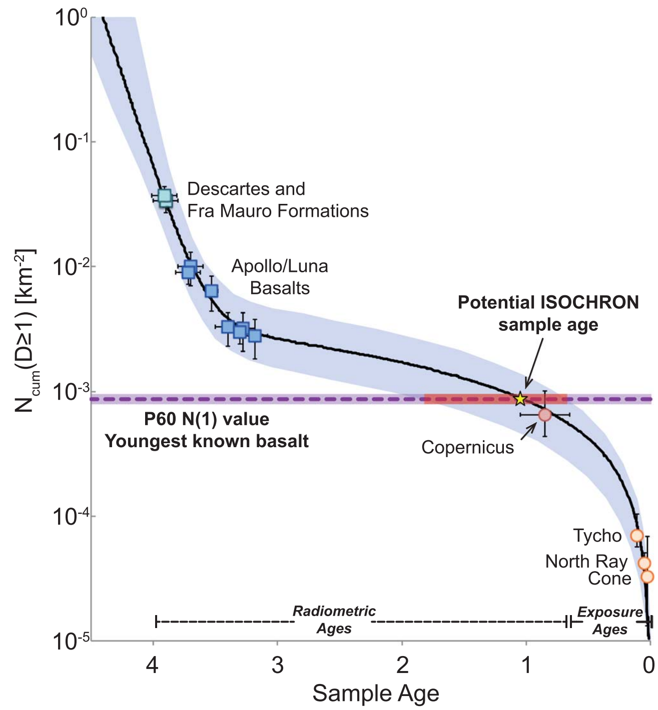

Figure 1. Lunar cratering chronology of Neukum (1983) relating radiometric and exposure ages of lunar samples to $N(1)$ values for each sampled unit. The blue shaded region shows the variation in fits for other chronology functions. The $N(1)$ for the P60 basalt is shown in purple, with the expected radiometric sample age range in red.

The Apollo and Luna sample collections are dominated by material older than 3.0 Ga, as demonstrated by laboratory measurements using a variety of radiogenic isotope chronometers. These materials include ancient highland rocks, old mare basalts, and basin impact rocks, which in turn are dominated by Imbrium basin ejecta (Stöffler et al. 2006).

Calibration points for samples and surfaces with ages of ∼3.2 and 1 Ga are missing from the lunar cratering chronology, resulting in uncertainty about the fit of the function for this time period. Different versions of the cratering chronology function place it higher or lower than the Neukum (1983) function (black curve in Figure 1), giving a range of solutions represented by the blue shaded region. Given the shallow slope on this part of the function, large differences in derived absolute model ages can result from small variations in $N(1)$ values measured on lunar surface units. At least one data point in this time period would allow better calibration of lunar chronology functions, as well as lunar-derived functions used for other planetary bodies (see also van der Bogert & Hiesinger 2020). ISOCHRON would return an ideal sample to improve this crucial planetary tool by sampling the youngest known basalt on the lunar nearside, the P60 basalt, for which the $N(1)$ value and its error bar are shown in purple (Figure 1). A radiometric sample age is expected to fall within the red bar, and, if consistent with the Neukum (1983) chronology function, would lie at the yellow star. A position to the right or left would require evaluation of the new sample age in comparison to other chronology functions or an update of the Neukum (1983) function.

An additional advantage to sampling a very young basalt is the possibility of calibrating the chronology over billions of years using one rock type (mare basalt), rather than relying on a combination of old basalts and young crater materials. The calibration points for <∼1 Ga are based on radiometric ages of impact glass and exposure ages for impact ejecta and material disturbed by secondary impacts. Ropy impact melt glass inferred to be from the Copernicus crater was sampled at the Apollo 12 landing site (Eberhardt et al. 1973; Alexander et al. 1976; Bogard et al. 1994; Barra et al. 2006) and calibrated against CSFD measurements both at Copernicus and on Copernican rays near Apollo 12 (Neukum 1983; Hiesinger et al. 2012; Iqbal et al. 2020). However, the radiometric age for these samples has a large error bar, and determining a CSFD for the ejecta blanket of an impact crater is complicated by target property differences and self-secondary impacts (van der Bogert et al. 2017; Zanetti et al. 2017; Xiao 2018). The cosmic-ray exposure ages of Apollo 17 samples from the Central Cluster and Light Mantle Deposit—features interpreted as related to the 2500 km distant Tycho crater (Drozd et al. 1977; Lucchitta 1979)—are tied to CSFD measurements at both the Taurus Littrow valley and Tycho crater (Neukum & König 1976; Hiesinger et al. 2012). Efforts to relate Apollo 15 samples to CSFD measurements at two craters in Mare Imbrium, Autolycus (Ryder et al. 1991) and Aristillus (Grange et al. 2013), are inconclusive owing to the difficulty in identifying suitable calibration regions around either crater (e.g., Hiesinger et al. 2016). Thus, without a highly accurate radiometric age (small error bars) that can be tied to a large, uniform site for the ∼1–3 Ga portion of lunar history, there is, and will remain, uncertainty in the timing of events that unfolded in the middle part of lunar history.

The Moon is likely to remain the only body beyond Earth for which we have planetary samples of well-known geological provenance for many years. Thus, the lunar cratering chronology has been adapted for use on other bodies in the solar system by incorporating the average impact velocity, surface gravity, and proximity to the asteroid belt to estimate differences in impact flux at these different bodies and allow absolute model age estimates for them on the basis of their crater densities (Figure 2; e.g., Bougher et al. 1997; Neukum et al. 2001; Hartmann & Neukum 2001; Marchi et al. 2009, 2012, 2013; Fassett et al. 2011; Schenk et al. 2012; Schmedemann et al. 2014). Such age estimates are applied to understanding the relative and absolute timing of geologic events and unraveling the surface histories of many other rocky bodies in the solar system, including Mercury (Fassett et al. 2012; Marchi et al. 2013), Venus (Bougher et al. 1997; Korycansky & Zahnle 2005), Mars (Hartmann & Neukum 2001; Shahrzad et al. 2019), and asteroids Ceres (Hiesinger et al. 2016, Bennu (Ballouz et al. 2019) and Vesta (O'Brien et al. 2014), and used in models of early solar system dynamics (Michel & Morbidelli 2007). Although cratering chronologies have been modeled from observations and extrapolations of asteroid/impactor size–frequency distributions (e.g., O'Brien et al. 2014), the lunar cratering chronology is the only available tool for estimating the absolute ages of these rocky surfaces and dating significant events in the geologic histories of rocky bodies.

For example, on Mars, our understanding of the timing of voluminous, shield-forming volcanism depends on the position and slope of the chronology function from ∼3 to 1 Ga (Phillips et al. 2001; Werner 2009). This period of intense volcanism is of great interest because it was likely closely coupled to substantial climate change, with the planet becoming increasingly dry and acidic over time owing to the addition of volcanic gases to the atmosphere; persistent surface water disappeared sometime in this ∼2 Ga period (Fassett & Head 2008; Carter et al. 2013; Niles et al. 2013; Kite et al. 2019). Determining

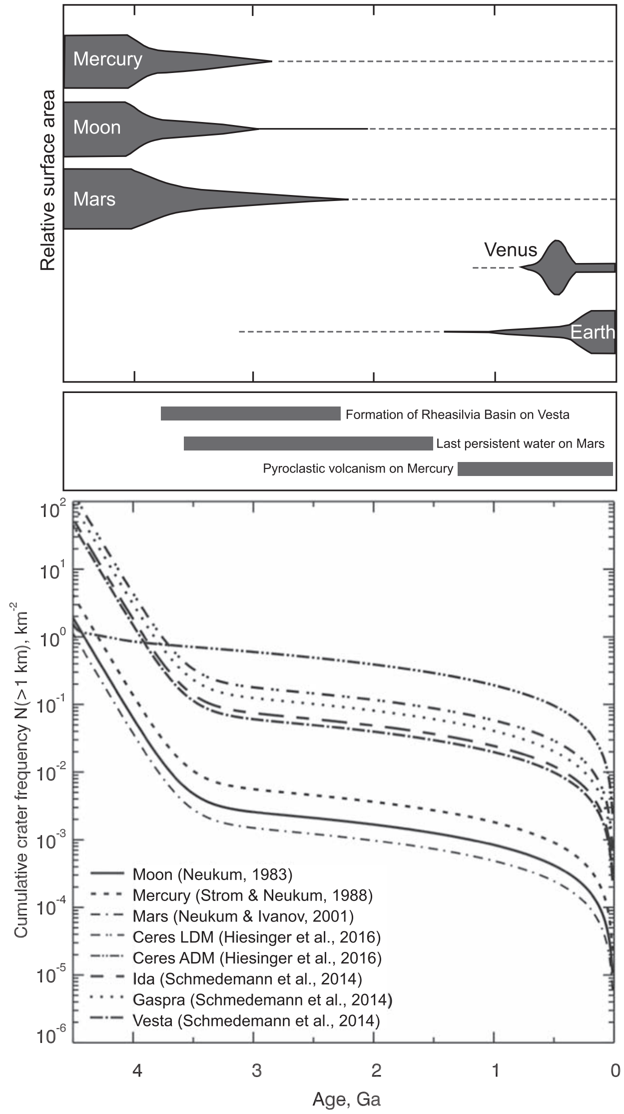

Figure 2. The lunar cratering chronology (solid black) is extrapolated for use on many solar system bodies. The flat slope of the function from 3 Ga to modern times, plus the absence of a calibration point in the 3–1 Ga time period, causes uncertainty in the absolute timing of major planetary events and our understanding of the absolute ages of the planetary surfaces (top; adapted from Head 1999).

when weather patterns changed, and thus when conditions became less hospitable to life on Mars, is currently possible only by extrapolation from the lunar cratering chronology. The new ISOCHRON calibration point(s) would thus yield insight into the timing of these and other planetary geologic events.

Similarly, understanding the history of crustal formation and volcanism on Mercury is complicated by the uncertainties in the lunar chronology during this mid-range of solar system evolution. Volcanism largely ceased during the Calorian Period on Mercury; there is over 2 billion yr of uncertainty in the modeled age of the end of the Calorian (Denevi et al. 2018). The youngest volcanic deposits on Mercury are thought to be within the basin Rachmaninoff (Prockter et al. 2010); there is ∼1 Ga of uncertainty in that age, such that Prockter et al. (2010) could constrain the timing of the cessation of volcanism only to the "second half of solar system history." Understanding the timing of volcanism is a major constraint used for models of Mercury's internal evolution (e.g., Hauck & Johnson 2019), and Mercury itself provides one of our end-members for understanding the evolution of the terrestrial planets.

Thus, to achieve goal 1, ISOCHRON would collect and return samples of one of the youngest examples of large-scale mare volcanism in order to obtain radiometric age dates with at least three geochronometers. These laboratory-obtained absolute ages would then be calibrated against the cumulative number of craters ⩾a reference diameter (usually 1 km) determined from the CSFD at the sample site. Existing image data meet requirements for these CSFD measurements and are used to guide the selection of an ideal landing site in the extensive and young P60 mare basalt unit, as defined by Hiesinger et al. (2010) and further examined by Stadermann et al. (2018). Details on the landing site location and characteristics are given in Section 3.1.

2.2. Goal 2: Determine the Late-stage Thermal and Magmatic Evolution of the Moon

Our understanding of lunar differentiation and evolution, in particular the lunar magma ocean model, is the foundation of the current paradigm for the interior evolution of one-plate planets such as Mars, Venus, and Mercury; differentiated asteroids; and the earliest stages of Earth's history, before the onset of plate tectonics (Elkins-Tanton 2012). However, the complete view of the thermal and chemical evolution of the Moon is obscured owing to the incomplete temporal and spatial sampling by Apollo and Luna. Samples of ISOCHRON's target young basalt would provide answers to key questions about the internal evolution of the Moon, crucial context for models of other one-plate planets, and a critical link between smaller differentiated asteroids and the terrestrial planets. Key questions would include the following. How do planets cool, and what are the mechanisms for recent mantle melting? How extensive are the interior heterogeneities produced by the lunar magma ocean? To what extent are magma ocean reservoirs rich in heat-producing elements involved in late-stage mantle melting? What was the extent and duration of mantle convection? How has the lithosphere thickened over time? How heterogeneous are the interior volatile reservoirs, and how are volatiles cycled? What are the mechanisms for planetary volatile depletion?

To address these questions, the youngest lunar basalts returned by ISOCHRON would be analyzed for major, minor, and trace element geochemistry and isotopic composition. The mission would also determine the in situ color properties of the landing site and surrounding basaltic terrain and relate them to existing compositional remote-sensing data sets. Together, these would establish the mineralogy, petrography, petrology, and elemental/isotopic compositions of a young lunar basalt.

The geochemistry of the young basalt at the ISOCHRON landing site would allow us to not only address the questions above but also place these samples within the local, regional, and global lunar geological and chronological context. No Apollo, Luna, or meteoritic igneous lunar sample is younger than ∼2.9 Ga (Borg et al. 2009; Elardo et al. 2014), meaning that we currently have no lunar samples from two-thirds of solar system history. ISOCHRON would deliver samples of the youngest flood basalt on the Moon with known geologic provenance that is directly relatable to remotely sensed data. These data would allow the mission to address multiple objectives of the Decadal Survey (NRC 2011; see Section 2.4).

Geochemical and isotopic data on the ISOCHRON basalt samples would allow for a new synthesis with previously returned samples and lunar meteorites. They would sharply clarify lunar mantle heterogeneity and yield insights into interior evolution (Elardo et al. 2015). ISOCHRON samples would provide critical data from which important insights, such as the depths of melting, mantle composition and mineralogy, magmatic processes, and distribution of heat-producing elements, can be determined and used to better understand the late-stage evolution of one-plate planets. From such inferences, aspects such as lithospheric thickening, solid-state mantle convection, and heat sources for melting (Wieczorek et al. 2006) can be more fully understood during a time period for which there are currently no constraints from samples.

The magmatic history of a planet reflects its composition, internal structure, and long-term thermal evolution. Melting of the lunar mantle during the main peak in mare magmatism ∼3.6 Ga ago (Hiesinger et al. 2010) is generally attributed to a combination of primordial heat, radiogenic heat production, and decompression melting from convection of a relatively hot mantle (Shearer et al. 2006). Younger magmatism, such as the young basalts found on the nearside (∼1.2 Ga; Morota et al. 2011) and irregular mare patches (potentially <100 Ma; Braden et al. 2014), require long-lived heat sources and/or melting mechanisms. However, thermal evolution models of the lunar interior are unconstrained during the time from ∼3 Ga to the present. Geodynamic models predicting an early cessation of mantle melting by ∼3 Ga and models predicting partial melting at the present time are all permissible within the uncertainties on key parameters (Snyder et al. 2000; Spohn et al. 2001; Zeithe et al. 2009; Laneuville et al. 2013). The recent thermal evolution of the lunar interior cannot be meaningfully constrained further without more data from young samples of the type that ISOCHRON would deliver.

Young basalts also record information on the abundances and heterogeneity of magmatic volatiles (H_2O, F, Cl, S, and C) in the lunar interior (Saal et al. 2008; McCubbin et al. 2015) and the role they play in recent melting. The volatile contents of lunar magmas and the role volatiles played in magma production and eruption are effectively unconstrained over the last few billion years. Are the young P60 basalts low-temperature, volatile-rich magmas capable of erupting from a cooler lunar mantle, or are they from deeper in the lunar interior, where sufficient heat is present to enable melting? Volatile measurements of these basalts would provide an unparalleled window into that history.

2.3. Goal 3: Test Models of Regolith Dynamics and Provide Ground Truth for Remote Sensing

Essentially, the entire lunar surface is covered by regolith, the debris of impact events that fragment bedrock into smaller and smaller pieces and redistribute its pulverized remains across the Moon. At each spot on the Moon, the regolith contains a treasure trove of information about the geologic history of that location and a history of its interactions with the space environment.

To achieve goal 3, the ISOCHRON-returned samples would include regolith developed on one of the youngest lunar mare basalts suitable for providing ground truth for remote-sensing data and characterizing the amount of local and foreign material. ISOCHRON would also measure in situ visible slopes and photometric ratios of regolithic soils at the landing site and compare them to ultraviolet (UV), visible (Vis), and near-infrared (NIR) remote-sensing data. The composition of lithic and glass fragments and the abundance of agglutinates; nanophase iron and its ratio–to–iron oxide content, or I_s/FeO; and other space weathering products within the regolith will identify materials transported to the landing site via vertical and lateral impact mixing.

Because the lunar surface is nearly all regolith, and most remote-sensing techniques penetrate only the topmost surface of a planet, regolith is the medium that nearly all of our remote-sensing measures. Thus, understanding how the regolith is generated, transported, mixed, and altered is of great value not just for the particular site from which that regolith was sampled but for the interpretation of the wealth of orbital data that recent lunar missions have supplied, as well as for future in situ resource utilization missions or studies.

2.3.1. How Does Ejecta Emplacement Modify the Surface of Planetary Bodies?

One of the tenets of lunar science is the model of how the regolith is mixed by "ballistic sedimentation" (Oberbeck 1975). All previous sample return sites were on ancient terrain; what is mixing like in a young one, far from a mare/highland boundary? What is the nature of the ray emplacement processes? By measuring the fraction of local versus distal material within a crater ray, ISOCHRON would test models of ejecta sedimentation processes and how mixtures of materials are measured in remote-sensing data.

Along with volcanism, impact cratering is among the most influential processes on airless bodies. Impact events influence the surface far beyond the crater itself; the rays of the Tycho crater stretch at least 2000 km (106° of arc; Dundas & McEwen 2007), and Hokusai's rays on Mercury extend 7000 km (164°; Ernst et al. 2018). Further back in time, the effects of large basins were essentially global in reach.

Rather than forming a simple blanket that covers the surface, ejecta from primary impact events reimpact the surface at velocities substantial enough (up to 2.4 km s^{-1} on the Moon) to scour the surface and dredge up and mix with local material. The model for how this process works was developed on the basis of Apollo 16 samples of the Cayley plains, a mixture of ejecta from the Imbrium basin (~1000 km away), and locally derived highland materials (Eggleton & Schaber 1972; Soderblom & Boyce 1972). This model for "ballistic erosion and sedimentation" makes predictions for the amount of local material that is incorporated into the ejecta deposit at a given distance from the primary crater (Oberbeck 1975).

At a small scale, this ballistic process dominates regolith gardening, whereby regolith at the upper few centimeters to meters is churned again and again, buried and exhumed until it matures after enough cumulative time spent at the surface, exposed to the solar wind and micrometeoroid bombardment (Gault et al. 1974; Speyerer et al. 2016). At a large scale, ballistic erosion and sedimentation have likely mixed the upper crust of the Moon to depths of kilometers to create the megaregolith (Haskin et al. 2003). Thus, impact mixing may be responsible for the observed compositional stratification of the upper crust, where the anorthositic norite that overlies purer anorthosite was created when the noritic lower crust or upper mantle was excavated by basin-forming impacts and mixed in this manner with the anorthositic highlands (Hawke et al. 2003). The ballistic sedimentation model has been tested using remote-sensing data, though tests of this type are dependent on our ability to determine the abundance of materials of varying compositions and maturity from reflectance spectra (Pieters et al. 1985; Blewett et al. 1997). ISOCHRON would provide an ideal and direct test of how local regolith is altered by distal impact events and how well remote-sensing data quantify mixed components within the regolith.

2.4. Traceability to Planetary Decadal Survey

The ISOCHRON mission is directly relevant to the themes and questions highlighted by the 2013–2022 Planetary Decadal Survey (NRC 2011). ISOCHRON samples and measurements would directly address crosscutting Decadal Survey themes 1 and 3, and the understanding gained by resolving the younger portion of the cratering chronology models for the Moon will feed into theme 2 studies as well. ISOCHRON closes critical science gaps in our understanding of the inner planets (chapter 5) and Mars (chapter 6) as identified in the Decadal Survey.

2.4.1. Building New Worlds

ISOCHRON goals 1 and 2 would directly address Planetary Decadal Priority Question 3: what governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? ISOCHRON geochronological measurements, coupled with remote-sensing measurements of the landing site, would greatly improve the understanding of the bombardment history of the inner solar system. Studying the mineralogy and composition of ISOCHRON-returned samples will expand our knowledge of the evolution of the lunar magma ocean and the volatile content of the lunar mantle. Together, the enhanced understanding of the lunar bombardment history and bulk composition will shed light on the timing of delivery of water to the inner planets.

2.4.2. Solar System Workings

All ISOCHRON goals address Priority Question 10: how have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time? ISOCHRON would constrain solar system bombardment rates as a function of time, measure the duration and chemical evolution of lunar volcanism, and directly test our models for space weathering and physical mixing rates in planetary regoliths.

3. Mission Concept Science Requirements

To advance the three ISOCHRON mission goals, samples must be returned from a landing site located on the most recent voluminous volcanic flows on the lunar surface while also providing access to Aristarchus ray material. Thus, ISOCHRON must (1) ensure that that these samples are obtained from a landing site that meets the requirements, (2) ensure that the character of the samples is appropriate for the required laboratory measurements, and (3) ensure that analyses of the returned samples are at the level of detail required to achieve mission objectives. The wealth of existing lunar remote-sensing data is ample for all required orbital reconnaissance for the ISOCHRON mission. The rich remote-sensing data sets from LRO and other lunar missions enable full science traceability from ISOCHRON samples to their global context.

Because mass is the primary driver for any mission design, it is critically important to define the minimum number of

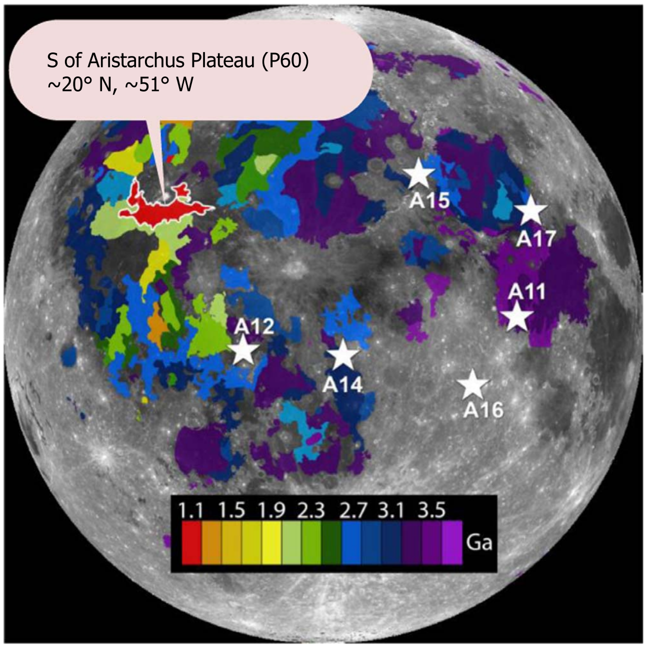

Figure 3. Lunar nearside with mare basalt units color-coded by absolute model ages (red = young; purple = old; Hiesinger et al. 2011). The ISOCHRON landing zone is unit P60, south of Aristarchus Plateau, with the youngest absolute model age of all mapped maria. White stars = Apollo landing sites.

samples and their types and features necessary in order to achieve this mission concept's science goals. In addition, a sufficient margin must be included in the design to accommodate potential complications. In the following sections, the requirements for the types of analyses that would be performed on ISOCHRON-returned samples are described. Although for sample scientists, more samples are always better, ISOCHRON's science goals could be achieved by returning as little as 200 g of new lunar material.

In the following subsections, we outline the geospatial, geochronological, and geochemical requirements for the ISOCHRON concept.

3.1. ISOCHRON Landing Site

ISOCHRON science goals require the return of regolith samples developed on a young mare basalt. Hiesinger et al. (2011) compiled their previous work mapping and dating many of the mare basalt flows on the Moon using CSFD measurements and the lunar crater chronology (Figure 1) to derive absolute model ages of each mapped unit. Figure 3 projects their basalt units, color-coded by model age, onto the lunar nearside. Many of the youngest mare flows erupted far west of the Apollo landing sites, with the most recent occurring within Oceanus Procellarum. The youngest expansive flood basalt unit, designated P60 (Figure 3), was emplaced south of the Aristarchus Plateau (Figure 4), roughly 1000 km from the nearest Apollo landing site, and has an absolute model age based on crater statistics of 1.2 $+0.32/-0.35$ Ga, within the current chronology data gap (Hiesinger et al. 2003). Stadermann et al. (2018) independently confirmed that P60 absolute model ages range from 1.03 to 2.81 Ga across the unit, and the ISOCHRON landing site targets the youngest zone from that work (Figures 4 and 5). Therefore, the laboratory-derived ages of the basaltic fragments returned by ISOCHRON would directly test the current family of lunar cratering chronology functions (Figure 1).

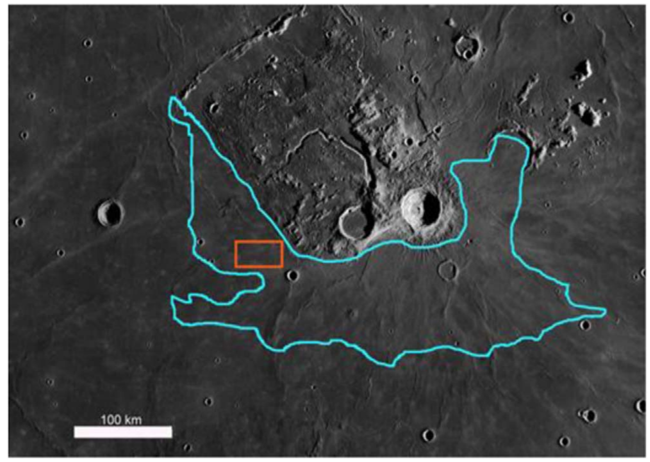

Figure 4. The LRO WAC image of the ISOCHRON landing site. The P60 area of Hiesinger et al. (2010) is outlined in cyan; the orange box includes the area shown in Figure 5.

The ISOCHRON landing site has a high likelihood of providing not one, but two, new ages. Our target site is located at the margin of a ray from the Aristarchus crater (the high-reflectance crater at center right in Figure 4), meaning that Aristarchus ejecta will likely be sampled by ISOCHRON. Samples of Aristarchus crater ejecta would provide an additional calibration point on the lunar chronology. The Aristarchus crater is thought to have formed between 1 Ga and 130 Ma ago (Figure 6; Zanetti et al. 2011; Stadermann et al. 2018). Correlating the CSFD from the continuous ejecta of Aristarchus with a sample age would provide a second robust young data point for the chronology and compensate for uncertainties in tying the Copernicus and Tycho craters to laboratory-derived ages for materials thought to be derived from these craters.

The specific region of P60 that would be targeted by ISOCHRON (Figure 5) is $\sim$200 km southwest of the Aristarchus crater and occupies $\sim$1400 km^2 in area. It is located at approximately 54°16 W, 22°48 N. Using current orbital data coverage for geologic context and hazard assessments, there are no resolvable blocks at the landing site, and the Diviner rock abundance is extremely low. Blocks are associated with fresh craters, and the nominal landing site avoids fresh craters.

Lucey et al. (2000) developed algorithms to estimate the iron and titanium content of mare basalts using Clementine multispectral data. Based on these algorithms, the site's basaltic regolith component is $\sim$18 wt% FeO, 10 wt% TiO_2 (derived from Clementine and Kaguya Multiband Imager data). Aristarchus ejecta are highly heterogeneous (e.g., Mustard et al. 2011); however, rim deposits radial to the landing site have $\sim$10 wt% FeO and $<$1 wt% TiO_2. The low FeO and TiO_2 contents of Aristarchus material near the landing site compared to those of mare basalt indicate that distinguishing the provenance of returned samples will be straightforward. Aristarchus excavated material from the eastern edge of the Aristarchus plateau, a volcanically mantled, uplifted highland (nonmare) crustal block (Zisk et al. 1977). The volcanism on the plateau itself dates to $\sim$3.7 Ga, but the source vents on the plateau may have been active over billions of years and ultimately contributed the younger flows in the P60 and adjacent regions. The Aristarchus impact event might have ballistically redistributed materials from the Aristarchus plateau as debris, including glass from the Moon's largest pyroclastic deposit

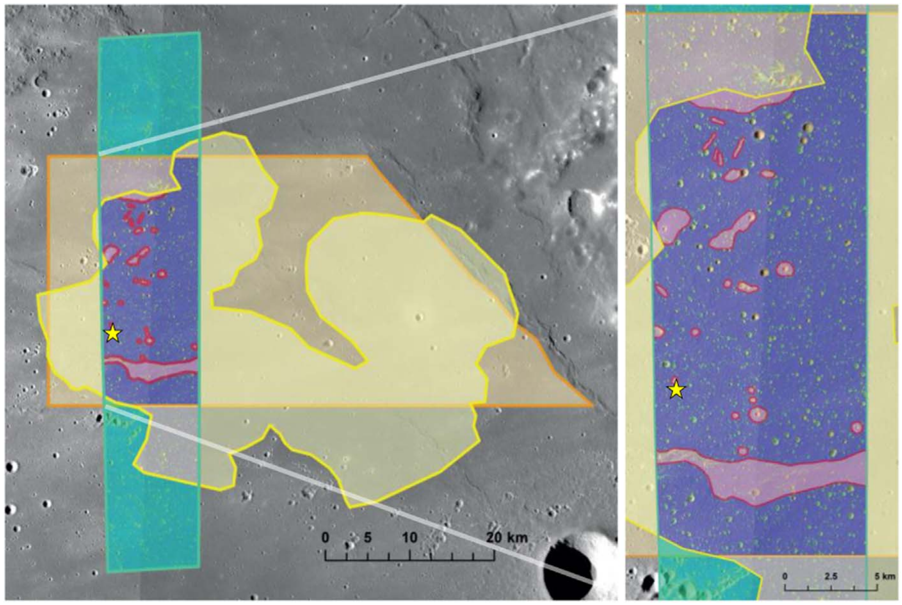

Figure 5. ISOCHRON would land (yellow star) within the region covered by the CSFD count areas of Hiesinger et al. (2003; orange) and Stadermann et al. (2018; yellow) that are also covered by LRO NAC stereo imagery and a digital terrain model (green). The remaining mostly blue area shows a slope map derived from the NAC DTM, where blue represents slopes of $<5°$. Red areas exclude secondary craters and chains where CSFD measurements would be difficult. The right panel is a closer view of the overlapping coverage areas.

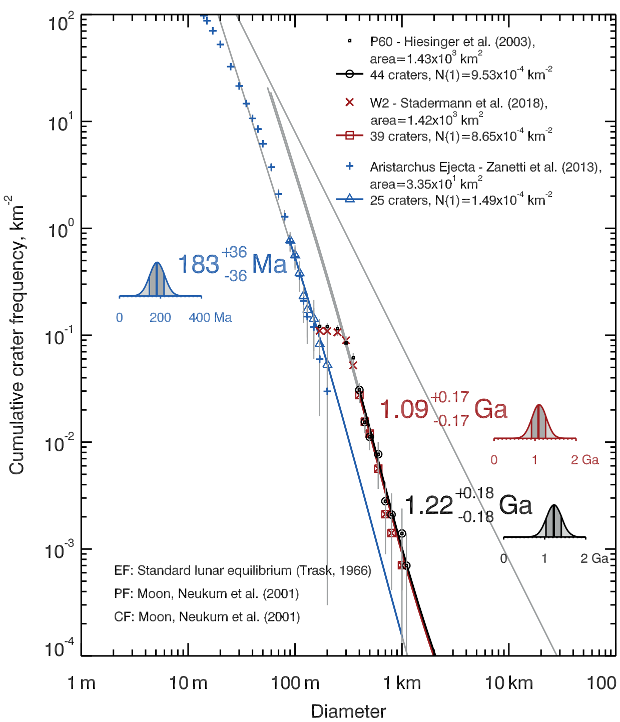

Figure 6. The CSFDs from the P60 (Hiesinger et al. 2003) and W2 (Stadermann et al. 2018) basalt units, as well as a CSFD for the continuous ejecta of the Aristarchus crater (Zanetti et al. 2013), which have been refit in cumulative form using the Neukum et al. (2001) chronology function and updated diameter ranges to avoid secondary crater contamination and applying Poisson timing analysis (Michael et al. 2016). The absolute model age of the P60/W2 basalt is ∼1.09–1.22 Ga, whereas the Aristarchus crater formed more recently.

(Gaddis et al. 2003) that could also be included in ISOCHRON's returned samples.

Assuming material transport and mixing through ballistic sedimentation (Oberbeck 1975), we would anticipate materials deposited as part of Aristarchus's ray system to be well mixed with the local basaltic materials and that this reworked regolith is between 0.5 and 2.5 m thick (Oberbeck 1975; Petro & Pieters 2004, 2006). Preliminary mixing calculations using the average P60 basalt and Aristarchus ray material as end-members suggest that regolith sampled at the site should contain ∼90 vol% local P60 basalt and 10 vol% Aristarchus ejecta. Thus, there is high confidence that ISOCHRON would return both P60 basalt and Aristarchus ejecta.

3.2. CSFDs at the Sampled Landing Site

To resolve the recent cratering chronology of the inner solar system, the samples collected by ISOCHRON must be linked to the CSFD of the landing site. The measurement of CSFDs is described in detail by, e.g., Hartmann (1966), the Crater Analysis Techniques Working Group (1979), Neukum (1983), and Hiesinger et al. (2000). A relative crater density at a reference diameter (e.g., $N(1)$ for 1 km diameter craters) is determined by fitting the CSFD with the lunar production function, extracting the $N(1)$, and calculating the absolute model age using the lunar chronology function (Neukum 1983; Neukum & Ivanov 1994; Neukum et al. 2001).

The geological unit is defined using both morphological and spectral characteristics. The measurement area is selected from within the geological unit on areas that are homogeneous, with as little topographic variation as possible and minimal slopes. Areas with secondary crater clusters and chains should be avoided or excluded from the measurement area. When accessing the morphologically and spectrally defined P60 basalt, it is important that the landing site avoid obvious secondaries from the Aristarchus crater. Recent CSFD studies using LROC data of the mare units sampled at the Apollo 12 landing site demonstrate that the visible ray material found there did not significantly change the chronological interpretation of the Apollo 12 basalt calibration points, although Copernicus ejecta caused a slight deflection of the smaller crater population in the CSFD consistent with its age (Hiesinger et al. 2012; Iqbal et al. 2020).

The CSFD measurements on the LROC wide-angle camera (WAC) mosaic (100 m pixel^{-1}; 100% site coverage; Stadermann et al. 2018) allow the measurement of craters with diameters larger than ∼400 m, while the Kaguya Terrain Camera mosaics (∼7 m pixel^{-1}, 100% site coverage) allow measurement of craters >∼40 m in diameter. The LROC narrow-angle camera (NAC) images (<∼2 m pixel^{-1}, 67°–73° incidence, 100% coverage of selected site) allow the measurement of craters down to at least 10 m in diameter, which is the lowest limit for the current lunar production and chronology functions. In preparation for an ISOCHRON mission, more detailed preparatory measurements can be made beyond those shown in Figure 6.

The CSFD measurements for the P60 and Aristarchus crater ejecta have been extensively studied (Figure 6; Hiesinger et al. 2003; Zanetti et al. 2011; Stadermann et al. 2018)). Based on the sampling site location constraints outlined above, ISOCHRON would be required to land within a 250 km^2 region of the P60 unit that is sufficient to provide a sample that is straightforward to relate with the CSFD of the basalt. Further refining this value requires a 250 km^2 region surrounding the landing site to be 100% covered by images at ⩽10 m pixel^{-1}, which are available from the Kaguya Terrain Camera.

3.3. Sample Geochronology Requirements

Crystallization age determinations on differentiated bodies such as the Moon are based on the decay of natural radioactive isotopes present in the samples. There are five isotopic chronometers that are commonly used in lunar chronology, including Rb–Sr, Sm–Nd, Lu–Hf, U–Th–Pb, and K–Ar (Ar–Ar). Although each of these systems has the potential to define an age, they can be variably susceptible to resetting and disturbance. Thus, robust crystallization ages are confirmed by application of more than one chronometer.

Lunar age investigations place minimum requirements on the character and size of the samples, as well as the total mass of samples needed to achieve the science goals. In general, an oblong crystalline mare basalt clast with a long diameter of ∼5 mm (mass ∼200 mg) is sufficient to (i) meet the sample requirements for chronological determinations using multiple techniques and (ii) produce a thin section for petrological characterization and complementary in situ chronology methods. Note that detailed petrologic characterization is critical for chronological investigations because it defines what lithology is dated and provides insights into the postcrystallization history of the sample that could disturb or reset some chronometers. For K–Ar, smaller individual (1–2 mg, 1–4 mm sized) granules to coarse sand–sized basalt or mineral separates can be analyzed for chronological and exposure age determinations. To obtain ages using Rb–Sr, Sm–Nd, Lu–Hf, and, to some extent, K–Ar, a sample must be crushed and sieved into three size fractions (150–75, 75–45, and <45 μm) and then separated into its constituent minerals. For mare basalts, these include plagioclase, ilmenite, and olivine and/or pyroxene.

Each isotopic system has strengths and weaknesses. The K–Ar and mineral isochron U–Pb systems are relatively easily disturbed by postcrystallization heating events, such as impact thermal metamorphism. Although the Rb–Sr, Lu–Hf, and particularly Sm–Nd system have proven to be highly reliable because they are very difficult to disturb by impact events, these systems have relatively large uncertainties associated with the long-lived parent isotopes. Furthermore, the latter two systems are subject to disturbance by neutron capture. Therefore, to obtain the most precise and reliable age, multiple chronometric systems must be applied to individual samples.

3.4. Geochemistry and Petrology Requirements

To understand the magmatic history of any lunar basalt, including that from P60, researchers must characterize the bulk and mineral compositions, investigate the texture and associations between minerals in the basalt, and measure the volatiles present within minerals in the sample. For the accurate characterization of the basalts and, if applicable, distinct lava flows present at the landing site, a minimum of 1 g of basaltic rock fragments are required for characterization by bulk chemical analysis and petrography based on experience with the Apollo 12 basalt suite.

To accurately classify a basaltic sample, bulk rock analyses of major, minor, and trace element abundances of igneous rock clasts at a minimum precision of 10% for major elements, 10%–20% for minor elements, and 20% for trace elements are necessary to provide the data vital to performing high-pressure and -temperature experimental investigations of the P60 basalt. Such experiments enable determination of the temperature and pressure conditions of the origin of the basaltic magma, enabling models of lunar thermal evolution and lithosphere thickening to be constrained. The required precisions are all easily achievable with the instruments available in terrestrial laboratories.

One polished section with surface areas of 1×1 (fine-grained) to 2×2 (coarse-grained) mm of each rocklet of interest is required to perform petrographic characterization and textural analysis, including crystal size distributions, in order to differentiate between possible origins (e.g., endogenous basalt, impact melt). Accordingly, 1 additional g of material is required to fully characterize the variability in basalt textures at the P60 site.

To perform in situ stable isotope (Cl, H, S) and volatile abundance (H, F, Cl, C, S) measurements to relate to the ages calculated in the geochronology section, a separate polished rocklet section of the surface area cited above is needed because high-quality analysis of volatile abundances in nominally anhydrous minerals, such as pyroxene and olivine, require epoxy-free mounting (indium or fields metal). Polished sections enable isotopic measurements as follows: δ^{37}Cl (±1‰, 2σ), δ^{34}S (±0.3‰, 2σ), δ^{18}O and δ^{17}O (±0.1‰, 2σ), Δ17O (±0.3‰, 2σ), and δD (±50‰, 2σ) by a large-geometry secondary ion mass spectrometer (SIMS) and/or nanoSIMS. The H, F, S, and Cl can be measured by SIMS to satisfactory levels of precision and accuracy.

3.5. Regolith Evolution Requirements

The ISOCHRON landing site lies within the rays of the Aristarchus crater (40 km in diameter; Figure 5), ∼165 km (8.25 crater radii) from the crater rim. The site was carefully selected to be within a region that provides a natural test for both the ballistic sedimentation model and the remote-sensing methods that are used to determine composition and maturity but outside of the resurfacing effects of large secondary craters (Figure 5), which could complicate the CSFD analysis.

Remote-sensing data suggest that the Aristarchus impact event occurred 130–280 million yr ago (Zanetti et al. 2017) in a low-iron target (∼10 wt% FeO), which provides a stark contrast to the older regional high-iron basalts (∼19–20 wt% FeO away from the main extent of the Aristarchus ejecta). These iron abundances were calculated from Vis–NIR Clementine and Kaguya Multiband Imager data (Lucey et al. 2000; Lemelin et al. 2015), and the methodology requires accounting for varying levels of soil maturity (i.e., varying levels of exposure to space weathering), which also varies across the region. Regolith at the ISOCHRON landing site is estimated by these same methods to contain 18 wt% FeO; a simple mass balance of the two end-members suggests that this site contains ∼10% Aristarchus ejecta, and 90% would be basalt. If, instead, the nonmare material contains as little as 5 wt% FeO, then the proportion would be 7% Aristarchus material and 93% basalt; no matter the true values, ISOCHRON would provide critical new information that would improve how maturity and composition are determined remotely.

The remotely determined values for mixing at the ISOCHRON landing site are in conflict with the expected mixing ratio, μ, which predicts the amount of foreign material mixed into the lunar regolith at a given distance from an impact crater due to ballistic sedimentation (Oberbeck 1975; Petro & Pieters 2004, 2006). This model ratio predicts that just 2% of the material at the landing site should be Aristarchus ejecta. The basalts at the P60 site are ideal to test the ballistic sedimentation model and resolve the conflict between remote-sensing measurements and model predictions. The ISOCHRON landing site is farther from a mare–highland boundary than was any Apollo landing site and far from large Copernican craters other than Aristarchus (Copernicus is over 1000 km or 22 crater radii away; Kepler is 635 km or 43 crater radii away) that would contaminate the site with other materials. Though their absolute age is uncertain, the relative youth and lack of superposed craters on the P60 basalts compared to any previous landing site also means that ISOCHRON will return samples that have experienced the least amount of lateral and vertical mixing by smaller craters. Thus, it is likely that this regolith sample will contain little besides P60 basalts and material transported by the Aristarchus event, providing a new end-member for regolith gardening that has occurred only after the impactor population waned and a direct measure of how much Aristarchus material was transported to the landing site.

ISOCHRON would quantify, for the first time, the relative contributions that known proximal (underlying mare basalt) and distal (Aristarchus crater impact) sources make to regolith bulk chemistry and grain-type populations and drive a requirement to return a total $\geqslant 5$ g of $\leqslant 1$ mm regolith to be used for mixture, exposure history, and ground-truth measurements. Material $\leqslant 1$ mm is required because it is this size fraction that dominates remote-sensing measurements. These data are required to be complemented by color imaging of the regolith at the landing site, obtained at least twice during the lunar day, at a spatial resolution that resolves 1 mm particles. Photometric comparisons of these images would enable an assessment of the regolith texture by characterizing how light scatters through the regolith (Blewett et al. 2014; Clegg-Watkins et al. 2016).

Guidance on the volume of the sample required for the laboratory measurements needed to meet these science objectives resides in three bodies of previous lunar regolith studies. The first of these is the series of coordinated analyses performed on a diverse set of mare and highland lunar regolith samples by the Lunar Soil Characterization Consortium (LSCC; Pieters et al. 2000; Noble et al. 2001; Taylor et al. 2001, 2010). This work is the standard for characterizing the degree to and mechanisms by which a given lunar soil has undergone the various processes of space weathering. The second are bulk chemical studies that have used mass balance/multiple least-squares major, minor, and trace element mixing models to unravel the characteristic regolith source regions contributing to a given soil or soils (Korotev & Kremser 1992). The third category consists of techniques using either implanted solar wind noble gas concentrations (Wieler 1998) or solar flare heavy ion track densities to measure the integrated near-surface exposure history of bulk soil samples, as well as individual grains.

The required sample mass is affected by the need to perform a coordinated analysis on multiple size fraction splits of a given bulk sample, which was a key approach of the original LSCC studies that resulted in significantly new scientific findings. Even with this additional levy on the sample size requirement, however, the LSCC studies performed their entire coordinated analysis protocols on total allocations of less than 150 mg of the <45 μm size fraction of a given lunar soil sample. This size fraction typically constitutes approximately 40 wt% of the <1 mm "soil" size fraction of a given bulk regolith sample (Pieters et al. 2000), with soil composing from 80 to 90 wt% of a bulk regolith sample (McKay & Ming 1989).

3.6. Potential Hidden Treasures: Aristarchus

Sample return missions offer something other mission types do not: the unique ability to study unexpected discoveries with all available techniques, not just those brought with the mission. A possible hidden treasure of the ISOCHRON samples are fragments derived from the Aristarchus Plateau, one of the most scientifically interesting localities on the Moon. Our remote sensing–based mixing models indicate that ∼10% Aristarchus material should be present at the ISOCHRON landing site.

Remotely sensed compositional data have shown that the Aristarchus Plateau is extremely enriched in Th, and Aristarchus ejecta would likely include fragments of impact melt, crystalline igneous rocks, and pyroclastic materials (Lucey et al. 1986; Hawke et al. 1991; Gaddis et al. 2003; Chevrel et al. 2009; Glotch et al. 2010). This enrichment would be easily distinguishable from P60 basalt. The materials excavated by the Aristarchus crater may be related to lunar silicic magmatism (Glotch et al. 2010), which is not well represented in the current sample collection, or possibly lunar magma ocean–derived highly enriched reservoirs (Hagerty et al. 2009), which would provide insight into an entirely different era of lunar magmatic evolution.

Silicic samples are also more likely to contain zircon; so, in the event that the Aristarchus samples contain zircon but are too small to date with other radiogenic systems (i.e., Sm–Nd), determining both an igneous crystallization age and an Ar–Ar age for the Aristarchus impact may be possible. A radiometric age for the Aristarchus impact would also allow ISOCHRON to provide a second CSFD calibration point for Copernican-aged crater materials in the lunar cratering chronology. In addition, this radioisotopic age determination would provide valuable input for questions about target property (van der Bogert et al. 2017) and self-secondary cratering (Zanetti et al. 2017) effects on CSFD measurements on ejecta versus impact melt deposits (Figure 6). These samples would also deliver information on volatile elements in highly differentiated lunar rocks and Th-rich pyroclastic glasses (Hagerty et al. 2009; Milliken & Li 2017) and provide ground truth for remotely sensed data sets such as the Lunar Prospector-GRS and Diviner silica enrichment determinations.

3.7. Relevance in Relation to Chang'e-5

Samples from the Em4/P58 basalt unit (Hiesinger et al. 2003; Qian et al. 2018) in northeastern Oceanus Procellarum were successfully returned to Earth by the Chang'e-5 mission in 2020 December. The remote-sensing characteristics of these basalts indicate that they are high-TiO_2 basalts with a thickness of about 50 m and an absolute model age of $\sim 1.53 \pm 0.027$ Ga that overlie older low-TiO_2 basalts (Qian et al. 2021). Thus, this material contrasts with the basalt that could be collected from P60. First, the P60 unit is even younger than Em4/P58, with an updated, statistically distinguishable absolute model age of ∼1.09–1.22 Ga (Figure 6). Second, the P60 basalt has a lower Ti content, as inferred from orbital remote-sensing data.

Analyses of P60 site materials would thus provide an even younger basalt reference point for the lunar chronology and allow a comparison of young basalt petrogenesis between two regions of Oceanus Procellarum. The possible acquisition of Aristarchus ejecta, where the origin via marked rays is well supported, also highlights the uniqueness of the selected landing site for the ISOCHRON mission. While the overarching science goals are similar between Chang'e-5 and ISOCHRON, young basalt materials are nevertheless still underrepresented in the sample collection, even after the success of the Chang'e-5 sample return.

4. Summary and Conclusions

The ISOCHRON concept to return samples of the youngest large mare basalt for age-dating and geochemical analysis would revolutionize the ability to assign exposure ages to rocky planetary surfaces that was founded on the samples returned by Apollo and Luna. Their petrology and geochemistry will enable assessment of the most recent voluminous lunar magmatism for the first time. Details of regolith evolution and mixing would be produced to provide direct tests of ballistic sedimentation and provide crucial ground truth that would enhance the science value of current and future remotely sensed data sets. It is to be hoped that NASA's Artemis program to return to the Moon and its related robotic programs currently in planning will provide an opportunity to achieve ISOCHRON's science goals.

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