The age of lunar mare basalts south of the Aristarchus Plateau and effects of secondary craters formed by the Aristarchus event

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Using crater size–frequency distributions (CSFDs) and careful discrimination of primary and secondary impact craters in the mare region south of Aristarchus Crater, we reexamined the age of unit ‘P60’, determined previously by Hiesinger et al. (2003) to be one of the youngest basaltic surfaces on the Moon. Owing to the apparently young age of these basalts, this region is a potential site for future sample return missions. We investigated this 55,000 km² region with Lunar Reconnaissance Orbiter Camera (LROC) images to assess potential variations in CSFDs across the unit, particularly in light of heavy contamination by secondary craters from Aristarchus Crater, and to determine the age(s) of P60 over its full areal extent. We are able to match, within one standard error, the previously determined age using approximately the same counting area. In addition, we defined twelve regions between the rays of secondary craters to determine if and how the ages of P60 might vary across the unit. For these inter-ray regions, we find a systematic progression of ages from west to east, ranging from youngest (∼1 Ga) in the west, to 1.8 Ga southwest of Aristarchus, to 2.2 Ga south of Aristarchus, and finally to 2.7 Ga southeast of Aristarchus. This variation in ages is not solely attributable to secondary cratering, indicating it must be at least partially due to volcanic resurfacing. The northwestern-most extension of P60 may belong to a different unit owing to topographic and crater distribution differences. Analysis of the summed CSFD for P60 provides evidence for emplacement of the younger basalts (<2.5 Ga) on top of an older surface of ∼3.6 Ga. We observe that ∼2–3 km diameter craters within an older mare unit are embayed by the younger lava flows, some of which are ‘ghost’ craters, with barely visible rims. In addition, we identified six volcanic vents that are possible sources for the younger P60 flow(s). This work indicates that volcanism spanned a significant range, from ∼3.6 Ga to 1.0 Ga ago across this region.

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1. Introduction

Mare volcanism is a fundamental geologic process that has persisted throughout much of the Moon’s history (e.g., Boyce, 1976; Wilhelms et al., 1987; Head and Wilson, 1992; Hiesinger et al., 2003, 2011). Establishing the timing of mare flood basalt emplacement is important for determining the thermal evolution of the Moon. Hiesinger et al. (2001, 2002, 2003, 2011) used crater size-frequency distribution (CSFD) measurements and absolute model ages (AMAs) to determine the timing of emplacement for mare units throughout Oceanus Procellarum on the lunar near side. On the basis of those findings, volcanism in this part of the Moon included basin-flooding flows 3.2–3.9 Ga ago, but also extended into the late Eratosthenian or early Copernican epoch, continuing until ~1 Ga ago (Hiesinger et al., 2003). Only the irregular mare patches have been determined to be possibly younger (Braden et al., 2014). The persistence of volcanic activity into the Copernican has major implications for the thermal evolution of the Moon. Young volcanic activity on the Moon indicates that the lunar mantle remained at least partially molten—or underwent partial melting in certain regions—for three billion years, or more. Thermal models must incorporate a long-lived heat source to allow for portions of the mantle to undergo partial melting until at least the late Eratosthenian (Shearer et al., 2006). In a model from Ziethe et al. (2009), volcanism on the Moon may have been able to persist until ~2 Ga ago.
ago because of the insulation effects of the megaregolith. Using new high-resolution imagery and more complete coverage of mare units, we reexamined the area south of the Aristarchus Plateau to investigate the age of the unit. Hiesinger et al. (2003) denoted this unit as ‘P60’ and found it to be the youngest unit on the Moon. We also seek to evaluate the effects of pervasive secondary craters from the younger Aristarchus Crater that superpose the P60 unit.

1.1. Regional context

The youngest mare units on the Moon, as determined by Hiesinger et al. (2003), occur in northwestern Oceanus Procellarum, predominantly in areas surrounding the Aristarchus Plateau. The Aristarchus Plateau and Marius Hills, located 300 km south of the plateau, are two major volcanic complexes that may be the sources for much of the central Oceanus Procellarum basalts (DeHon, 1979). These basalts are estimated to be between 250 m and 1 km thick (DeHon, 1979). Oceanus Procellarum has many sinuous rilles that indicate large volumes of basaltic lava erupted throughout the region (Cattermole, 1996). The mare basalts south of the Aristarchus Plateau, covering an area from 17°N to 26°N and 39°W to 56.5°W (Fig. 1), are among the youngest basalts on the Moon, with an AMA of 1.2 Ga for a unit named P60 (Hiesinger et al., 2003). This 1.2 Ga AMA is surprisingly young, considering Hiesinger et al. (2003) concluded that the flux of mare basalts was highest in the late Imbrian, after which the volcanic flux decreased sharply and probably became episodic (Hiesinger et al., 2003).

P60 borders on the Aristarchus Plateau borders to the north (Fig. 1), where the 42-km-diameter Aristarchus Crater formed along the northern part of P60 at the edge of the Aristarchus Plateau, excavating and ejecting basalts, older mare material beneath the basalts, and Plateau basement material (Zanetti, 2015). Aristarchus Crater ejecta superposes P60 basalts and is thus clearly younger than P60, most likely forming in the range of 160 to 280 Ma ago (Neukum and König, 1976; Zanetti et al., 2011, 2017). The 38-km-diameter Herodotus Crater lies to the west of Aristarchus Crater and along the northwestern edge of P60. Herodotus, however, is filled with basalt and is older than, or coeval with, the P60 basalts. On the Aristarchus Plateau, north of Herodotus Crater, are Vallis Schröteri and the informally named Cobra Head vent. The Cobra Head vent is one of the most prominent volcanic vents on the Moon and is thought to be the source vent for a large portion of Oceanus Procellarum basalts (Whitford-Stark and Head, 1977). The Marius Hills lie ~250 km to the south of the P60 region. Two other large, young impact craters, Kepler, located 500 km to the southeast of P60 at 8°N 38°W, and Copernicus, 500 km to the east of Kepler at 10°N 20°W, also contributed to the secondary crater population in the mare south of Aristarchus Plateau (Fig. 2).

1.2. Determining the age of unit P60

The absolute model age of the P60 region was most recently determined to be 1.20 Ga using CSFD measurements by Hiesinger et al. (2003), who defined regions of Oceanus Procellarum according to spectral units using a Clementine color ratio composite and designated the region south of Aristarchus as

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**Fig. 1.** LROC WAC low-sun global mosaic showing unit P60 (white) and the count region (black) defined by Hiesinger et al. (2003). The inset shows the location of this region on the Moon.

**Fig. 2.** High-sun angle LROC WAC mosaic showing Aristarchus, Kepler, and Copernicus craters. White arrows show secondary rays extending from Kepler and Copernicus to the P60 unit. Detail (NAC frame M1127426785) shows a secondary crater chain within a ray from Aristarchus Crater.
unit P60 (see also Pieters, 1978). Using Lunar Orbiter IV images, Hiesinger et al. (2003) selected a small subarea of the P60 unit that had minimal secondary crater contamination and counted all craters that were not obvious secondaries. The 1.20 Ga AMA makes the P60 region the youngest unit of the areas measured and reported by Hiesinger et al. (2003), and the youngest units on the nearside (Hiesinger et al., 2001, 2002). This 1.2 Ga AMA differs significantly from a previous estimate by Boyce (1976), who used the degradation of craters to estimate the ages of basalt flows in Oceanus Procellarum, but is marginally closer to crater degradation age estimates of Zisk et al. (1977).

Crater degradation uses the erosional profile of the largest craters in a region to estimate the age of the surface (Boyce and Dial, 1975). The amount of degradation is quantified (described by Boyce and Dial, 1975) and related to a theoretical crater diameter that is eroded to a 1° regional slope. This theoretical diameter is then related quantitatively to the age of the surface. The age reported by Boyce (1976) for the basaltic south of Aristarchus was 3.2 Ga ± 0.1 Ga. The discrepancy in age between Boyce (1976) and Hiesinger et al. (2003) may reflect fundamental differences in the two approaches of surface age determination. The region mapped by Boyce (1976) almost completely overlaps with the P60 unit from Hiesinger et al. (2003), further supporting that the discrepancy in age reflects differences in age determination approaches used by Boyce (1976) and Hiesinger et al. (2003). Though it should be noted that using crater degradation methods, Boyce et al. (1974) inferred a young age for mare basalt in Oceanus Procellarum, northwest of the Marius Hills region, of 1.7–2.5 Ga.

Zisk et al. (1977) also studied the geology and stratigraphy of the Aristarchus Plateau and surrounding regions using crater degradation methods. They divided the region south of the Aristarchus Plateau into three units on the basis of Lunar Orbiter and Apollo 15 images, instead of one homogeneous unit as Hiesinger et al. (2003) and Boyce (1976) defined the area. As such, the ages found by Zisk et al. (1977) for the P60 region varied from 2.7–2.8 Ga in the western portion of the area, to 3.1 Ga directly south of Aristarchus Plateau, to 3.3–3.4 Ga in the east (Zisk et al. 1977). This variation in age could possibly be a result of secondary crater contamination or it could be taken as evidence that unit P60 is not a single homogeneous mare basalt flow unit. The ages Zisk et al. (1977) found for this unit are roughly consistent with age estimates for global lunar mare basalt emplacement, and their upper bound of ages is comparable to the age found by Boyce (1976).

1.3. Effects of secondary craters

When an impactor strikes the surface of a planetary body and ejects material, ejecta falls back and re-impacts the surface, thereby generating secondary craters (e.g., Shoemaker and Hackman, 1962; Oberbeck and Morrison, 1973; McEwen and Bierhaus, 2006). Secondary craters have distinct physical features that distinguish them from primary craters. Secondaries typically occur in clusters, or rays, and have asymmetric ejecta patterns and crater shapes (Shoemaker and Hackman, 1962; McEwen and Bierhaus, 2006). Secondary craters can skew the results of CSFD measurements if they are not excluded from the statistics (Neukum et al., 1975; Neukum, 1983; McEwen and Bierhaus, 2006; Zanetti et al., 2017).

Determining ages in the P60 region is difficult because of heavy secondary crater contamination, particularly from Aristarchus Crater, but also from other nearby Copernican craters, including Kepler and Copernicus (Fig. 2). As suggested by McEwen and Bierhaus (2006), many craters that appear also to be primary could be isolated secondaries and may affect CSFD results. These isolated secondaries can be difficult to discern from primary craters if they do not occur in clusters, or along rays, or if they do not exhibit visible asymmetry that would belie a secondary origin. However, distinguishing isolated secondary craters from degraded primary craters remains difficult or impossible because they can be morphologically very similar.

Neukum et al. (1975) argued that secondary crater contributions to crater counts are negligible when excluding obvious secondaries. Obvious secondaries are defined here to be those in clusters and rays, or those having herringbone-shaped and elongated ejecta patterns. Despite evidence from Neukum et al. (1975) that undetected secondaries may not be significant, our models for the age of the P60 unit consider the effects of secondary contamination because P60 is close to Aristarchus and has many secondary rays crossing it (Fig. 2). On the other hand, Quantin et al. (2016) studied the Martian crater Gratteri and determined that about half of all secondary craters occur in rays, but concluded that counting primary craters along with ‘field secondaries’ (i.e., secondary craters not in rays) still provides useful and relevant chronometric data. Werner et al. (2009) estimated that counting all secondary craters would increase the model age by a factor of two at most. However, they determined that the percentage of unrecognized secondary craters is typically less than 5% of all craters in a given count, and would thus have negligible effects on age determination, being less than the statistical error of the model age.

The physical properties of the target surface are also important when estimating the age of units (McEwen and Bierhaus, 2006; van der Bogert et al., 2017). If the target properties change across the unit, for example, from thin regolith overlying basalt to older and thicker regolith, the resulting difference in small crater diameters, within the strength regime, could cause an apparent variation in derived AMAs. We minimize this effect by considering only craters larger than 400 m in diameter.

1.4. Objectives and approach

In this work, we had three primary objectives: (1) to test the previous determination that basalts within the P60 unit have a young age of 1.2 Ga; (2) to determine if the entire P60 unit has the same AMA as the subarea measured by Hiesinger et al. (2003); and (3) to test the effects of secondary impact craters on the determination of basalt ages using CSFD analyses, including if there are effects from undetected distal secondaries from Kepler and Copernicus. When investigating Objective 2, we saw variability in AMAs across the P60 unit, which spawned two additional objectives: (2a) to determine if there is spatial relationship to the variation in ages; and (2b) to determine if there are volcanic sources within the P60 unit that may be the source of some of the variability.

We addressed the first objective by obtaining a CSFD for the same count area that was used by Hiesinger et al. (2003) and comparing the results. Further, we obtained a CSFD for the entire P60 region and determine if the age is comparable to that of the smaller count area. The second objective is addressed by defining inter-ray regions that have no detectable secondary craters within their bounds. We checked for variation between these inter-ray regions using CSFD analyses. We completed the second objective by creating a crater point density map of the P60 region. This map treats each crater as a single point and determines the density of craters in a given region, thereby allowing us to quantify variations in the spatial density of impact craters across the P60 unit. Since we saw variations in AMAs across P60, we tested Objective 2a by determining that the variations in AMAs of the inter-ray regions cannot be correlated with latitude, longitude, or distance from Aristarchus Crater. When testing Objective 2b, we found several volcanic vents within
and near P60, and we found a spatial relationship of the AMAs with proximity to the volcanic vents.

Lastly, we investigated the effects of secondary craters on age determination to satisfy Objective 3. All CSFDs we generated were screened for evidence of secondary contamination. We investigated regions of heavy secondary contamination in the crater point density map, and compared them with regions of low secondary contamination (i.e., the inter-ray regions). Finally, we obtained CSFDs for radial rings extending from Aristarchus, including both primary and secondary craters to determine the effect increasing distance from Aristarchus has on overall crater density.

2. Methods

2.1. Definition of the P60 unit

The P60 unit was defined using the Clementine multispectral color ratio composite (756–409 nm/756 + 409 nm as red, 756 nm/409 nm as green, 409 nm/562 nm as blue) (Fig. 3). The spectral characteristics represented in the color composite reflect variations in Ti content and soil maturity, and along with changes in morphology, have been shown to be effective in distinguishing mare units (e.g., Whitford-Stark and Head, 1980; Hiesinger et al., 2000, 2003). While the P60 unit as defined by the Clementine color ratio composite is a mare unit distinct from the surrounding mare basalts, Pieters (1978) used telescopic spectral reflectance data to characterize this unit as two basalt types: hDSA and LBG-. hDSA is characterized by a medium-high ultraviolet/visible (UV/VIS) ratio, dark albedo, strong 1 μm band, and absent 2 μm band. LBG- is characterized by a low UV/VIS ratio, bright albedo, and average 1 μm band, while the 2 μm band is absent (Pieters, 1978). The geochemical meaning of the 1 μm and 2 μm bands is complex, composed of several individual absorption features such that distinguishing them is difficult (Pieters, 1978).

As we defined the P60 unit in this work (Figs. 1 and 3), we attempted to replicate the region used in Hiesinger et al. (2003). There are some distinct differences, notably the inclusion of unit P48, and the exclusion of a lobe on the western edge of P60. Overlying regions of the Hiesinger et al. (2003) P60 region were omitted or modified based on consideration of simplicity and maintaining continuity in the point density map, which requires a 5 km buffer from the edge of the unit. As drawn, our unit overlies the vast majority of the original P60 unit as drawn by Hiesinger et al. (2003).

2.2. Crater size-frequency distribution (CSFD) measurements

The use of CSFD measurements is an established method for remotely determining the ages of planetary surfaces such as the Moon (e.g., Neukum and Horn, 1976; Neukum, 1983; Hiesinger et al., 2000, 2003). This method is based on the size-frequency distribution of inferred primary craters within a given region to determine the relative age of a surface, which is calibrated to surfaces whose ages are known independently (i.e., by radiometric measurement of ages of samples from known locations on the Moon; Stöffler and Ryder, 2001; Stöffler et al., 2006). We used the global Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) mosaic to determine the CSFD of the P60 unit, and standard crater-counting techniques detailed in previous papers (e.g., Crater Analysis Techniques Working Group, 1979; Neukum, 1983; Neukum and Ivanov, 1994; Hiesinger et al., 2000; Neukum et al., 2001). The pixel scale of the WAC mosaic is 100 m/pixel and limits the minimum size of craters that we can reliably count to approximately 400 m in diameter. We used CraterTools in ArcGIS (Kneissl et al., 2011) and CraterStats2 (Michael and Neukum, 2010) for our age determinations, applying the production and chronology functions of Neukum et al. (2001). All CSFD measurements are presented as cumulative crater frequency plots using cumulative fits with statistical 1σ uncertainties (‘PDF’, Michael and Neukum, 2010; Michael et al., 2016). Poisson age analysis, which is an exact prediction not relying on binning of the data as required for cumulative fits, was also performed and presented in Table A1.

In our CSFD analysis of unit P60, we first compare our counting methods and results to previous results of Hiesinger et al. (2003). We defined the P60 unit and recreated the count area used by Hiesinger et al. (2003). By counting the primary craters in the same count region used by Hiesinger et al. (2003), our results can be directly compared to their work.

All the craters within the entire P60 unit, categorized as primary or secondary, were then counted to estimate the frequency of secondary craters as well as to assess possible age variations (apparent variations in AMAs) across the P60 unit. Secondary craters

![Fig. 3. Clementine color ratio image overlain on LROC WAC low-sun global mosaic shown in Fig. 1. P60 is shown in white.](image-url)
were distinguished by the presence of secondary rays, clusters, and herringbone patterns in ejecta, or oblong crater shapes. Next, we subtracted the area of all secondary crater clusters and rays from the entire primary count area, and created a CSFD of all the primary craters in the remaining ‘primary area’ of P60, allowing a ‘whole-P60’ AMA to be obtained for all craters, minus obvious secondaries and the area the secondaries contain.

We counted all craters larger than 400 m in diameter (D). Although this data set likely excludes many secondary craters (D < 400 m), it almost certainly includes some secondary craters (D > 400 m). From the analysis of Singer et al. (2014), we estimate that even as far away as 100 km from the rim of Aristarchus, secondaries from Aristarchus as great as 2 km in diameter are possible. However, there are few craters in the entire P60 region that are larger than 2 km. For craters > 400 m in diameter, we also do not expect there to be a significant effect of target properties on the crater diameters that we measured (e.g. McEwen and Bierhaus, 2006; van der Bogert et al., 2017).

We marked areas of known secondary craters and created inter-ray regions, which we defined as areas with mostly primary craters, and then calculated CSFDs for these inter-ray regions. A CSFD with secondary contamination may have a slope steeper than expected by the primary crater production function because some secondary material ejected at low velocities preferentially makes small craters (i.e., secondary craters; McEwen and Bierhaus, 2006), so as we consider smaller and smaller crater sizes, the proportion of total craters that are secondaries should increase. The inter-ray regions, then, should exhibit normal slopes in accordance with the production function (Neukum et al., 2001), indicating minimal contamination from secondaries. The secondaries that do remain in the crater counts presumably would have little influence on the age determination (Werner et al., 2009; Quantin et al., 2016), but we test this presumption (see Discussion).

2.3. Spatial crater density variation tests

To test the variation in the crater density of both primary and secondary craters as a function of distance from the rim of Aristarchus Crater, we used concentric 25-km-wide rings in P60 to bin the data. Using these concentric rings, we were able to determine how the total number of craters changed with distance from Aristarchus. We created CSFDs to achieve an ‘AMA’ of the ring. This ‘AMA’ has no physical significance, since we deliberately include secondary craters. However, it allowed us to see how the abundance and distribution of craters changed with distance from Aristarchus.

Point-density maps also allow testing for crater density differences between secondary rays and inter-ray regions. Point density maps take into account only the number of craters, independent of their diameter, and show how crater density varies across the rays and inter-ray regions in the P60 unit. This type of map can be used to assess or quantify the effects of age differences and/or secondary contamination in terms of craters per unit area. The number of crater centers within a specified search radius of a cell determines the value of the cell. In our point-density maps, we used a 100 m by 100 m cell size to match the resolution of the WAC mosaic. We used a search radius of 5 km to balance seeing overall trends and local variations in the unit. The number of craters found within one search radius of the cell is divided by the search area, and creates a ‘crater density’ for the cell in craters per km². Within 5 km of the boundary of P60 boundary effects lead to false crater densities, thus we have trimmed the extent of the crater density map to 5 km within the boundary of P60.

2.4. Volcanic vents

Volcanic vents on the Moon are generally characterized by broad low-slope cones consistent with low viscosity, fluid erup-
tions (Head, 1976). The vents are readily seen in low-sun angle images or LROC NAC high-resolution digital terrain models (DTMs) as depressions of circular to elliptical, elongate, or irregular shape, commonly situated in the center of a larger topographic high that can be broad, as in a small shield volcano. We searched for evidence of volcanic vents in and around the P60 unit as potential sources for the mare basalts that exist there.

3. Results

We first present results for CSFD analysis of the P60 count area replicated from Hiesinger et al. (2003). We compare this replicated count area CSFD to the CSFD of the primary craters of the whole P60 region. Next, we present results from twelve inter-ray regions that occur between secondary rays from Aristarchus, allowing us to address variations in AMAs across the unit. Third, we present several possible volcanic vents within and near the P60 unit. Lastly, we present results from crater counts of concentric rings around Aristarchus Crater in P60 and a crater density map in order to assess variation in crater density with radial distance from Aristarchus Crater and assess the effects of secondary craters from Aristarchus within the P60 region. Cumulative fits for CSFDs are presented here, while Poisson fits are presented in Tables A1, A2, and A3. The differences between the cumulative fits and the Poisson fits range from 50 to 350 Ma (Table A2), but are on average about 170 Ma for the inter-ray regions.

3.1. Hiesinger et al. (2003) count area vs. whole P60 primary crater CSFD

To confirm the age determination of Hiesinger et al. (2003) and to calibrate our counting methods to their work, we recounted the exact same area used in that study (Table 1 and Fig. 4). We determined an AMA of 856 ± 180 Ma (N(1) = 7.17 × 10^{-4}), which is within the uncertainty of the 1.2 ± 0.32 Ga (N(1) = 1.01 × 10^{-3}) AMA of Hiesinger et al. (2003). Uncertainties on AMAs are statistical 1σ uncertainties (Michael and Neukum, 2010). Thus, we reproduced the AMA of Hiesinger et al. (2003), indicating that the basals of this count area are indeed very young. The PDF age for this count region is 987 ± 220/−190 Ma (Table A1).

In contrast, when including all craters in the P60 region and upon separating the primary and secondary craters, we found that the CSFD for the entire P60 region (primary craters) is best fit by two model ages for two different crater size ranges (Table 1, Fig. 5). The shape of the curve resembles a resurfacing curve, as described by Hartmann et al. (1981), Neukum (1983), and Michael and Neukum (2010). Craters with diameters between 400 m and 1200 m are best fit by an AMA of 1.83 ± 0.04 Ga (N(1) = 1.53 × 10^{-3}). Larger craters, between 3 km and 10 km are fit with an AMA of 3.58 ± 0.07/−0.12 Ga (N(1) = 6.23 × 10^{-3}). At diameters of 1.5–2.0 km we observe craters that are embayed by lavas and some that are ‘ghost’ craters—craters that are filled with lava just enough that their rim is still visible through the lava flow. When using Poisson PDFs, the AMAs change to 2.04 ± 0.04/−0.04 Ga for the smaller primary crater size range, 3.59 ± 0.08/−0.14 Ga for larger primary crater size range. To assess the effects of including secondary craters in the CSFD analysis, we consider an extreme the inclusion of all of the mapped secondary craters. If we combine primary and secondary craters in a single CSFD, along with the primary and secondary areas, we obtain an AMA of 3.42 ± 0.01 Ga, with a N(1) of 3.90 × 10^{-3}, and a Poisson PDF of 3.41 ± 0.0063 Ga, and the resurfacing evident in the selective primary crater CSFD is no longer clear.

3.2. Inter-ray count area CSFD analysis

In the areas between secondary rays and secondary crater chains across P60, we selected twelve additional count areas, des-

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**Table 1**

AMAs for P60 unit.

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (km²)</th>
<th>Crater Retention Age; N(1)</th>
<th>Model Age (Ga)</th>
<th>Error (Ga)</th>
<th>Fit Range</th>
<th>Number of Craters Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiesinger et al. (2003)</td>
<td>1.43E+03</td>
<td>1.01E−03</td>
<td>1.20</td>
<td>+0.32/−0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replicated Hiesinger et al. (2003)</td>
<td>1.50E+03</td>
<td>7.17E−04</td>
<td>0.856</td>
<td>+0.18/−0.18</td>
<td>300 m, 1.0 km</td>
<td>136</td>
</tr>
<tr>
<td>P60 Primary and Secondary</td>
<td>5.50E+04</td>
<td>3.90E−03</td>
<td>3.42</td>
<td>+0.01/−0.01</td>
<td>400 m, 1.2 km</td>
<td>6294</td>
</tr>
<tr>
<td>P60 Primary, craters 0.4–1.2 km</td>
<td>4.18E+04</td>
<td>1.53E−03</td>
<td>1.83</td>
<td>+0.04/−0.04</td>
<td>400 m, 1.2 km</td>
<td>2107</td>
</tr>
<tr>
<td>P60 Primary, craters 3.0–10.0 km</td>
<td>4.18E+04</td>
<td>6.23E−03</td>
<td>3.58</td>
<td>+0.07/−0.12</td>
<td>3.0 km, 10.0 km</td>
<td>10</td>
</tr>
</tbody>
</table>

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**Fig. 5.** CSFDs for the entire geographic extent of the P60 unit. The best-practice reduced-area measurement for primary craters in P60 (red in Fig. 6a), excluding areas affected by secondaries is shown in red with AMAs of 1.83 ± 0.04 Ga and 3.58 ± 0.07/−0.12 Ga. For comparison in black, is the CSFD of the entire unit (yellow and red in Fig. 6a) without excluding secondaries or areas affected by secondaries with an AMA of 3.42 ± 0.01 Ga. The equilibrium function is the standard lunar equilibrium of Trask (1986), while both the production and chronology functions are from Neukum et al. (2001).
Fig. 6. (a) The P60 region (white outline) and all craters counted in the measurements, where primary craters are red and secondary craters are yellow. The interior white areas are the inter-ray regions used to investigate regional AMA variation and are labeled 1 for W1, 2 for W2, etc. The Hiesinger et al. (2003) count area roughly overlaps W2. (b) Color-coded inter-ray regions according to their AMA in cumulative crater statistics. Darker red indicates older ages, while lighter shades indicate younger ages. Two groups of inter-ray regions with similar ages are outlined in dashed white ellipses. Base map is LROC WAC low-sun angle global mosaic and has a pixel scale of 100 m/pixel.

W1–12, from west to east, denoted with ‘W’ to reflect this order. Accordingly, W1 is the westernmost inter-ray region and W12 is the easternmost (Fig. 6a). These inter-ray regions contain primary craters with no obvious secondaries and serve as a measure of how the surface age might vary across the unit (Fig. 6b). The AMAs from these inter-ray regions range from 1.03 Ga to 2.81 Ga (Fig. 7 and Table 2).

W1 is in the northwestern-most part of the P60 unit, west of the Aristarchus Plateau, and just north of the count region used in Hiesinger et al. (2003). W1 is 996 km² in size and has an AMA of 2.39 ± 0.29 Ga and $N(1) = 2.01 \times 10^{-3}$ (Fig. 7a and Table 2). Its PDF age is 2.63 ± 0.36 Ga (Table A2). We used a crater diameter fitting range of 500 m to 1200 m to include large craters in the W1 region, and to exclude possible undetected secondary contamination at crater diameters less than 500 m.

W2 largely overlaps the Hiesinger et al. (2003) count area, although it does not extend as far west as that count area (and in our calibration area). W2 covers 1420 km² and, when fitting craters between 400 m and 1 km diameter, has an AMA of 1.03 ± 0.16 Ga and $N(1) = 8.66 \times 10^{-4}$ (Fig. 7b and Table 2). Its PDF age is 1.10 ± 0.18 Ga (Table A2). Our crater fit begins at 400 m, which is the smallest diameter crater we can reliably count using the LROC WAC mosaic with a resolution of 100 m/pixel. The largest craters in this region are approximately 1 km in diameter, creating the upper limit for our AMA fitting range.

W3 is located in the southwestern-most corner of the P60 unit and is an inter-ray region of 1130 km². We fit craters with diameters between 400 m and 1 km for an AMA of 1.82 ± 0.25 Ga and $N(1) = 1.53 \times 10^{-3}$ (Fig. 7c and Table 2). The PDF age is 1.89 ± 0.26 Ga (Table A2).
Fig. 7. CSFDs in cumulative form with cumulative fits from the inter-ray regions (see also, Table 2). (a) W1, (b) W2, (c) W3, etc. The equilibrium function is the standard lunar equilibrium of Trask (1966), while both the production and chronology functions are from Neukum et al. (2001).
Table 2
AMAs for inter-ray regions. Elevations are approximated using DLG100 (Scholten et al., 2012).

<table>
<thead>
<tr>
<th>Region</th>
<th>Elevation (m)</th>
<th>Area (km²)</th>
<th>Crater Retention Age; N(1)</th>
<th>Model Age (Ga)</th>
<th>Error (Ga)</th>
<th>Fit Range</th>
<th>Number of Craters Fit</th>
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<tr>
<td>W1</td>
<td>−1900 to −1800</td>
<td>9.66E+02</td>
<td>2.01E−03</td>
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<td>+0.29/−0.29</td>
<td>400 m, 12 km</td>
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<td>−1900 to −1800</td>
<td>1.42E+03</td>
<td>8.66E−04</td>
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<tr>
<td>W3</td>
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<td>1.13E+03</td>
<td>1.53E−03</td>
<td>1.82</td>
<td>+0.25/−0.25</td>
<td>400 m, 1 km</td>
<td>52</td>
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<td>W4</td>
<td>−1630 to −1590</td>
<td>5.87E+02</td>
<td>1.34E−03</td>
<td>1.60</td>
<td>+0.32/−0.32</td>
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<td>W5</td>
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<td>400 m, 800 m</td>
<td>46</td>
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<td>1.90</td>
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<td>1.17E−03</td>
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<td>+0.38/−0.38</td>
<td>400 m, 700 m</td>
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<td>+0.32/−0.32</td>
<td>400 m, 800 m</td>
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<td>W12</td>
<td>−1530 to −1510</td>
<td>6.29E+02</td>
<td>2.14E−03</td>
<td>2.55</td>
<td>+0.49/−0.58</td>
<td>500 m, 700 m</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 8. LROC Digital Terrain Model (DTM) (WAC GLD100, Scholten et al., 2012) overlain with 200 m contour intervals (black lines). White dots indicate vent locations in and near the P60 unit (Table 3).

W4 covers 587 km² and is located north of W3 and south of Herodotus A. Using a fit of craters with diameters between 400 m and 800 m, we found an AMA of 1.60±0.32 Ga and N(1)=1.34×10⁻³ (Fig. 7d and Table 2), and the PDF age is 2.01±0.29 Ga (Table A2). We limited the fit of the AMA for W4 to 800 m although there are a few craters larger than this diameter in the W4 inter-ray region because the craters >800 m do not appear to lie along the same production function as the smaller craters, but there are too few craters >800 m in W4 to evaluate whether the distribution of the larger craters would be consistent with a resurfacing process and an older-age fit to the larger craters.

W5 is located at approximately 20°N and 50°W and is 902 km² in size. The W5 region has an AMA of 2.08±0.29 Ga and N(1)=1.74×10⁻³, using a fit of craters from 400 m to 800 m (Fig. 7e and Table 2). The PDF age is 2.18±0.31/−0.32 Ga (Table A2). As for regions W3 and W4, we excluded several craters with diameters larger than 800 m.

W6 is directly south of W5 and east of W3. The W6 region is 962 km² in size and has an AMA of 1.90±0.27 Ga and N(1)=1.59×10⁻³ (Fig. 7f and Table 2). This 1.90 Ga AMA is derived from a fit of craters from 400 m to 1 km in diameter. The PDF AMA for W6 is 2.01±0.29 Ga.

W7 is centered on 17.8°N 48.6°W. It is 381 km² in size, and has an AMA of 1.39±0.38 Ga and N(1)=1.17×10⁻³ (Fig. 7g and Table 2). Its PDF age is 1.50±0.46/−0.38 Ga (Table A2). The fit range of craters used for W7 is relatively small, from just 400 to 700 m, but fits the production function well.

W8 is located at approximately 20°N 45°W, and is 394 km² in size. We used a fit of craters from 425 m to 800 m to derive an AMA of 2.55±0.41/−0.45 Ga and N(1)=2.14×10⁻³ (Fig. 7h and Table 2) and PDF age of 2.87±0.31/−0.46 Ga (Table A2). In the W8 region, craters with diameters smaller than 400 m are excluded from the count because of the difficulty of clearly resolving such craters.

W9 covers 518 km² and is located directly east of Aristarchus Crater in the northeastern-most part of the P60 region. By fitting the craters between 400 m and 800 m, we obtained an AMA of 1.56±0.32 Ga and N(1)=1.31×10⁻³ (Fig. 7i and Table 2) and a PDF age of 1.91±0.39 Ga (Table A2). In the W9 region, there are no craters larger than 800 m.

Southeast of W9 is the 728 km² region W10. We used craters with diameters between 400 m and 800 m to obtain an AMA of 2.73±0.30/−0.37 Ga and N(1)=2.29×10⁻³ (Fig. 7j and Table 2). The PDF age is similar, 2.80±0.37/−0.45 Ga (Table A2).

W11 is 280 km² in area and slightly northeast of W10. W11 has an AMA of 2.81±0.38/−0.61 Ga and N(1)=2.37×10⁻³ when its CSFD is fit for craters with diameters between 400 m and 550 m (Fig. 7k and Table 2). Craters larger than 550 m are overproduced relative to the production function, but it is unclear if this is a
result of resurfacing or simply poor statistics. Again, the PDF age is similar, $2.86 \pm 0.35/−0.50$ Ga (Table A2).

The last inter-ray region, W12, is located just east of W10 at $21.5^\circ$N and $41^\circ$W. W12 is $629$ km$^2$ in size, has an AMA of $2.55 \pm 0.49/−0.58$ Ga and $N(1) = 2.14 \times 10^{-3}$, and is located on the eastern edge of the P60 unit (Fig. 71 and Table 2). The AMA for this region was derived using a fit of the production function to craters with diameters between 500 m and 700 m. Craters smaller than 500 m appear to include secondary contamination, causing the CSFD slope to be steeper than a normal primary production function. The PDF age is $2.85 \pm 0.36/−0.50$ Ga (Table A2).

3.3. Volcanic vents within and near P60

The elevations of regions of P60 can reveal where it is possible to have volcanic sources, and where the lava from those sources may have come. Elevations across P60 range from approximately $−2100$ m to $−1400$ m, generally sloping downward from east to west (Table 2). Inter-ray region W1, in the northwestern part of P60, is located at the lowest elevation at $−2100$ m, and W9, in the northeast and closest to Aristarchus Crater, is at the highest elevation, $−1425$ m. Region W2, due west-southwest of Herodotus and south of W1, occurs at $−1900$ to $−1800$ m elevation. Inter-ray regions in the southwestern part of P60 (W3–7) all occur between about $−1800$ to $−1700$ m. Regions in the eastern part of P60 (W10–12) all lie in the range $−1440$ to $−1500$ m. Region W8, which lies between the eastern and western groups of inter-ray regions occurs at an intermediate elevation of approximately $−1600$ m.

Within and around the P60 unit, we identified six volcanic vents (Fig. 8 and Table 3), which we labeled V1 through V6 in order from west to east. These vents may have been sources for flows in P60. Several of these vents are irregular shaped depressions and situated on a broad, low profile volcanic construct, as shown in Fig. 9 for V1. V1 is a small shield volcano within inter-ray region W5, which is $∼12$-km-wide at its base and $∼200$-m-high with a large, irregular-shaped summit depression $3 \times 5$ km in size. Vent V3 occurs along the inside rim of a flooded $18$ km diameter crater at $−1530$ m (flood level). Vent V1 occurs at an elevation of $−1660$ to $−1640$ m (surrounding basalt surface), Vent V4 occurs at $−1490$ m, and vent V5, at $−1400$ m, south of inter-ray region W9. Vent V6 occurs at an elevation of $−1620$ m, the southest and west of the vents identified here. The vents are not covered or obviously embayed by the lava flows surrounding them.

3.4. Distribution of primary and secondary craters with distance from Aristarchus

To assess potential effects of secondary craters on subarea crater counts in the P60 region, we divided the entire area according to distance from the rim of Aristarchus and analyzed the CSFDs using all craters, primary and secondary (Fig. 10). Because the number of secondaries falls off with distance from the primary crater, we might expect the ‘apparent’ AMAs fit to the CSFD data, when the secondaries are part of the fit, to decrease away from Aristarchus, although we ascribe no actual age significance to the retrieved AMAs. We use these values (Figs. 11, 12 and Table 4) as a proxy to evaluate the influence of secondary craters as a function of distance from Aristarchus Crater.

The rings are plotted by distance from Aristarchus in Fig. 12. The ‘apparent’ AMAs range from $3.78 \pm 0.06/−0.11$ Ga in the 25 km ring, to $3.04 \pm 0.12/−0.18$ Ga in the 225 km ring, decreasing with distance from Aristarchus out to the limits of the P60 unit at 230 km along a relatively smooth trend, with a correlation coefficient of $−0.908$. Again, we emphasize that these AMAs do not represent ages of the surface in these rings, but represent a measure of the maximum effects of incorporating secondaries in the CSFD analysis. The inter-ray regions of our primary crater counts, on the other hand, show no systematic variation as a function of distance from the rim of Aristarchus (correlation coefficient $−0.007$; Fig. 14). The secondary crater distribution becomes dominated by ray-structures as the distance from Aristarchus Crater increases. The ‘apparent’ AMAs from concentric rings thus average the secondary craters in rays with primary craters in the given ring.

The point-density map for craters in P60 has areas of high crater density emanating radially away from Aristarchus Crater.
These areas correlate strongly with the secondary rays from the crater (e.g., Fig. 2). These high-crater-density regions have more than 0.6 craters per km², whereas low-crater-density inter-ray regions have less than 0.3 craters per km².

4. Discussion

In this section, we first discuss the age one might infer for the entire P60 unit based on CSFD analysis of the same subarea as defined and analyzed by Hiesinger et al. (2003), and based on a summed CSFD for areas that exclude obvious secondary craters in the form of prominent ray material from Aristarchus, Copernicus, and Kepler. We then consider the inter-ray regions and the results of their CSFDs, and how they vary across P60. We also consider the effects of secondary craters by examining radial variations of CSFDs and crater density distributions away from the rim of Aristarchus Crater and across the P60 unit. Finally, we briefly discuss the implications of volcanic vents within and near P60.

4.1. Age of the P60 unit

We independently confirmed the results of Hiesinger et al. (2003) for the same count area using different base images. The image mosaic used in this study has a resolution of 100 m/pixel, whereas the Lunar Orbiter IV images used by Hiesinger et al. (2003) have resolutions ranging from 60 to 150 m/pixel. Both the Lunar Orbiter images and LROC WAC mosaic have moderate incidence angles and good contrast. Hiesinger et al. (2003) specifically chose their count area to avoid other parts of P60 that are intensely contaminated with rays and secondary craters from Aristarchus, Copernicus, and Kepler.

The summed CSFD exhibits a 'kink' in the CSFD at crater diameters of ~2–3 km, and for craters >3 km diameter the data can be fit with a 3.58 +0.12 /−0.07 Ga isochron. This type of kink in the data suggests that the larger craters record an older basalt surface that was covered and mostly, but not completely, resurfaced by the younger basalt flow(s) that now make up the surface of P60 (see e.g., Michael and Neukum, 2010). The 3.58 Ga age in the P60 region is somewhat similar to crater degradation age measurements by Boyce (1976), who found an age of 3.2 Ga for a region corresponding approximately to P60. Several 1.5–2.0 km craters appear to be embayed by a lava flow, indicating that these craters pre-date the flow. Other craters of similar size are ghost craters with only their rims showing through the younger basalt flow. The embayed craters and the ghost craters both indicate that there are indeed at least two flows in this region, with eruption ages separated in time by about 2 Ga. Using the rim heights of the embayed and ghost craters, we estimated that the flow embaying these craters was ~50-m-thick using the method of Pike (1977).

From the crater count of the entire P60 area minus areas determined to be affected by secondary effects of Aristarchus, the CSFD can be fit by an isochron of 1.83 +0.04 Ga for craters of diame-

![Fig. 10. LROC WAC low-sun global mosaic with outline of P60 in thicker white line. In thinner white lines are the concentric rings in 25 km increments from Aristarchus Crater, where the number in each ring refers to the outer boundary of that annulus. The corresponding CSFDs are shown in Fig. 11.](image-url)
Fig. 11. CSFDs for data binned according to concentric rings from Aristarchus Crater (Fig. 10). (a) 25 km ring, (b) 50 km ring, (c) 75 km ring, etc. The equilibrium function is the standard lunar equilibrium of Trask (1966), while both the production and chronology functions are from Neukum et al. (2001).
ter 400–1200 m (Fig. 5). The range of AMAs for the twelve inter-ray regions is actually quite substantial, however, ranging 1.03 to 2.81 Ga. The variation in ages across the unit is significant, raising the question of whether this variation results from the inclusion of undetected secondary craters in our inter-ray region counts, or from the existence of multiple basalt flows with similar composition, but different ages.

4.2. Variation in inter-ray region AMAs across P60

Inter-ray regions exhibit a wide distribution of AMAs, ranging from 1.03 Ga in W2 to 2.81 Ga in W12. If this variation reflects real age information, it could indicate flows of different ages within the P60 unit. As suggested by the differing inter-ray region AMAs, a series of different flows could either have come from a single vent, such as Vallis Schröteri, and vary systematically east to west across the unit with increasing distance from the source, or the flows could have emanated from the various vents across the unit, and vary more sporadically. However, several of the vents (V1, V2, and V5) are too low in elevation to have fed the higher surfaces (i.e., those above −1600 m; W9–W12). The higher-elevation surfaces on the eastern side of P60 must have been sourced from higher-elevation vents (e.g., V6 likely sourced the surface at W9 because of proximity and elevation relations). The absence of correlation of AMAs with proximity to any one of the identified vents suggests that the variation in ages was not caused by a single source with multiple flows. There is also no statistically significant variation in the AMAs as a function of latitude for all 12 of the analyzed subareas. There is a weak correlation observed longitudinally, with AMAs generally increasing from west to east (Fig. 14), especially if W1 is eliminated as an outlier, because it lies at a significantly lower elevation than other P60 inter-ray regions.

Alternatively, if the inter-ray regions’ AMAs are affected by unrecognized secondaries from Aristarchus, Copernicus, and Kepler, the AMAs would be expected to be higher in regions closer to those respective craters. If this were the case, the AMA of W9 (AMA of 1.56 ± 0.32 Ga) should be greater than that of W3 (1.82 ± 0.25 Ga AMA). W9 is the closest inter-ray region to Aristarchus Crater and therefore W9 would be expected to have one of the highest AMAs. W9 instead has one of the lower AMAs, although its PDF AMA is 1.91 Ga. Moreover, W1, 180 km from the rim of Aristarchus, and W12, 176 km from the rim of Aristarchus, are some of the farthest from Aristarchus and have among the oldest AMAs. Although W12 is closer to Copernicus and Kepler and thus could be affected by secondaries also from those craters, W1 is the farthest away from Copernicus and Kepler. Regions W5, W6, and W7, which are close to each other, have decreasing AMAs with increasing distance from Aristarchus, but the decrease is much greater than expected if undetected secondaries were included in the CSFD analysis. Although the inclusion of undetected secondaries in our CSFD analysis of the inter-ray regions remains a possibility, we conclude that such inclusion is most likely not the cause of the majority of variations in AMAs for subareas across P60. There is no correlation between distance from the rim of Aristarchus and the AMA of the inter-ray region AMAs (with or without W1). Instead, we conclude that significant variations occur in the inter-ray region ROIs corresponding to east-west location, with several spatially related groups with similar ages (W3–W7; W8 and W10–W12 in Fig. 6). Below we consider the significance of the ages of some of these groups.

The group of inter-ray regions including W8 and W10–W12 occurs in the southeastern part of the P60 unit and has an average AMA of 2.6 ± 0.22 Ga. All of the AMAs of these inter-ray regions are within uncertainty of this value. Using the Poisson age analysis, this group would have an average AMA of 2.8 Ga. The other significant group of inter-ray regions W3–W7 occurs in the southwestern part of P60 and surrounds vent 2, which is located within W5. These inter-ray regions have an average AMA of 1.76 ± 0.13 Ga (PDF average = 1.87 Ga). Although other inter-ray regions do not have as clear of a relationship to a particular vent, these two groupings are consistent with the hypothesis that the variation in AMAs between inter-ray regions is the result of multiple flows from different volcanic centers within P60.

Inter-ray regions W2, W4, W7, and W9 have AMAs that, within uncertainties, are similar to the 1.2 Ga AMA suggested by Hiesinger et al. (2003) for P60 and by our replicated count of their work. These regions are, however, widely distributed across P60 and only W9 is related by proximity to a potential source vent that is likely different from the sources of W2, W4, and W7. We cannot rule out the possibility that inter-ray regions W1, W2, and W9 each represent separate flows.

4.3. Variations in primary and secondary craters with distance from the Aristarchus Crater

If secondary craters were most abundant closest to the proximal ejecta blanket and decreased with distance from Aristarchus,
we would expect to see a trend in AMAs (used as a proxy for the relative influence of secondary craters) with the greatest values close to the crater and decreasing with distance away from it. As anticipated, the data shows a steadily decreasing AMA with increasing distance from Aristarchus (Figs. 11 and 12). These AMAs are consistently considerably higher than those of primary-only counts (inter-ray regions W1–W12), and of nearby units from Hiesinger et al. (2003). The unit directly south of P60, as mapped and dated by Hiesinger et al. (2003) is P51 and has an AMA of $1.85 \pm 0.37$ Ga. The concentric ring furthest from Aristarchus Crater (Fig. 11) and the one with the lowest AMA, 3.04 Ga (including known secondaries, Fig. 12), is for the outermost ring and is still considerably higher than the age found for P51, indicating that a significant amount of secondaries are still present in the outermost ring CSFD. The AMAs for these nine subareas follow a linear correlation with increasing distance from Aristarchus, with $R^2 = 0.91$. If we exclude the 200-km-radius ring, which extends 175–200 km from the Aristarchus Crater rim, $R^2$ improves to 0.96. This variation clearly reflects the effects of secondary craters from Aristarchus falling off as a function of distance from Aristarchus, superposed on the primary crater population.

The observation of variation in crater distribution as a function of distance from Aristarchus is not obvious when compared qualitatively to the point density map (Fig. 13), where local crater density appears to be quite irregular. In the point density maps, secondary rays are highlighted as well as regions of P60 that are perhaps shielded from Aristarchus secondaries by the Aristarchus Plateau. The regions of highest crater density are located within secondary rays, but are not obviously of higher density closer to Aristarchus Crater. In fact, some of the highest areas of crater density are located at the outskirts of the P60 unit, farthest south from Aristarchus Crater.

### 5. Conclusions

Using different data sets, we independently confirmed the results of Hiesinger et al. (2003) that show the unit P60 contains one of the youngest basalt flows on the Moon. We also analyzed inter-ray regions across the entire P60 unit to expand the count area investigated by Hiesinger et al. (2003) and to explore potential age variations across the unit. With the exclusion of secondary craters and rays from Aristarchus from other nearby craters, P60 yields an average age of 1.83 Ga. However, when inter-ray areas are analyzed separately, they reveal a trend of increasing AMAs from west to east, ranging from $>2$ Ga in the southeast to 1.8 (1.4–2.1 Ga) in the southwest, and several apparently younger areas spread across P60 (1.03–1.56 ± 0.2–0.4 Ga). Given the presence of at least six volcanic vents, in addition to the regional grouping of ages, we conclude that volcanic activity was not limited to one volcanic vent or eruption.

The basalt surface underlying P60 was emplaced at about 3.6 Ga ago. This volcanism occurred concurrently with the peak of lunar mare volcanism (Hiesinger et al., 2003). Following the emplacement of this unit, there is little evidence for continued volcanism in the P60 region until renewed emplacement at 2.5 Ga, ending by $\sim1$ Ga. This resurfacing is reflected both in the CSFD measurements and morphologically via observations of embayed and ghost craters of about 2 km diameter across the unit.
Finally, our investigation revealed that the secondary crater population decreases systematically with distance from Aristarchus, as expected. If these craters were included in the CSFD measurements, they would produce spuriously high AMAs close to Aristarchus Crater, with decreasing effects extending away from the crater, but also reaching beyond the boundaries of P60 (Fig. 12). The overall effects of secondaries, with clumped concentrations along rays from Aristarchus, are readily seen in a crater density distribution map (Fig. 13). The use of inter-ray measurements areas was crucial for our investigation of the geological history of unit P60.

Acknowledgments

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Appendix

(Table A1, Table A2, Table A3)

Table A1

AMAs for P60 unit using cumulative crater statistics and Poisson statistics represented as probability density functions (PDFs).

<table>
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<th>Region</th>
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<th>Model age (Ga)</th>
<th>Error (Ga)</th>
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<th>Error, PDF (Ga)</th>
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<td>+0.32/−0.32</td>
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<td>0.967</td>
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<tr>
<td>P60 Primary and Secondary</td>
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<td>3.42</td>
<td>+0.01/−0.01</td>
<td>3.88E–03</td>
<td>3.41</td>
<td>+0.0063/−0.0063</td>
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<td>1.83</td>
<td>+0.04/−0.04</td>
<td>1.71E–03</td>
<td>2.04</td>
<td>+0.045/−0.044</td>
</tr>
<tr>
<td>P60 Primary, craters 3.0–10.0 km</td>
<td>6.23E–03</td>
<td>3.58</td>
<td>+0.07/−0.12</td>
<td>6.48E–03</td>
<td>3.59</td>
<td>+0.080/−0.14</td>
</tr>
</tbody>
</table>

Table A2

AMAs for inter-ray regions using cumulative crater statistics and Poisson statistics represented as PDFs. Elevations of inter-ray regions approximated using DLG100 (Scholten et al., 2012).

<table>
<thead>
<tr>
<th>Region</th>
<th>Elevation</th>
<th>Crater retention age: N(1)</th>
<th>Model age (Ga)</th>
<th>Error (Ga)</th>
<th>Crater retention age, PDF: N(1)</th>
<th>Model Age, PDF (Ga)</th>
<th>Error, PDF (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>−1900 to −1800 m</td>
<td>2.01E–03</td>
<td>2.39</td>
<td>+0.29/−0.29</td>
<td>2.21E–03</td>
<td>2.63</td>
<td>+0.27/−0.31</td>
</tr>
<tr>
<td>W2</td>
<td>−1900 to −1800 m</td>
<td>8.66E–04</td>
<td>1.03</td>
<td>+0.16/−0.16</td>
<td>9.24E–04</td>
<td>1.10</td>
<td>+0.18/−0.18</td>
</tr>
<tr>
<td>W3</td>
<td>−1760 to −1740 m</td>
<td>1.53E–03</td>
<td>1.82</td>
<td>+0.25/−0.25</td>
<td>1.58E–03</td>
<td>1.89</td>
<td>+0.26/−0.26</td>
</tr>
<tr>
<td>W4</td>
<td>−1760 to −1740 m</td>
<td>1.34E–03</td>
<td>1.60</td>
<td>+0.32/−0.32</td>
<td>1.47E–03</td>
<td>1.76</td>
<td>+0.36/−0.36</td>
</tr>
<tr>
<td>W5</td>
<td>−1800 to −1720 m</td>
<td>1.74E–03</td>
<td>2.08</td>
<td>+0.29/−0.29</td>
<td>1.82E–03</td>
<td>2.18</td>
<td>+0.31/−0.32</td>
</tr>
<tr>
<td>W6</td>
<td>−1775 to −1700 m</td>
<td>1.59E–03</td>
<td>1.90</td>
<td>+0.27/−0.27</td>
<td>1.68E–03</td>
<td>2.01</td>
<td>+0.29/−0.29</td>
</tr>
<tr>
<td>W7</td>
<td>−1760 to −1740 m</td>
<td>1.17E–03</td>
<td>1.39</td>
<td>+0.38/−0.38</td>
<td>1.26E–03</td>
<td>1.50</td>
<td>+0.46/−0.38</td>
</tr>
<tr>
<td>W8</td>
<td>−1630 to −1590 m</td>
<td>2.14E–03</td>
<td>2.55</td>
<td>+0.41/−0.45</td>
<td>2.43E–03</td>
<td>2.87</td>
<td>+0.31/−0.46</td>
</tr>
<tr>
<td>W9</td>
<td>−1450 to −1400 m</td>
<td>1.31E–03</td>
<td>1.56</td>
<td>+0.32/−0.32</td>
<td>1.60E–03</td>
<td>1.91</td>
<td>+0.39/−0.39</td>
</tr>
<tr>
<td>W10</td>
<td>−1540 to −1500 m</td>
<td>2.29E–03</td>
<td>2.73</td>
<td>+0.30/−0.37</td>
<td>2.36E–03</td>
<td>2.80</td>
<td>+0.27/−0.35</td>
</tr>
<tr>
<td>W11</td>
<td>−1540 to −1500 m</td>
<td>2.37E–03</td>
<td>2.81</td>
<td>+0.38/−0.61</td>
<td>2.41E–03</td>
<td>2.86</td>
<td>+0.35/−0.50</td>
</tr>
<tr>
<td>W12</td>
<td>−1530 to −1510 m</td>
<td>2.14E–03</td>
<td>2.55</td>
<td>+0.49/−0.58</td>
<td>2.41E–03</td>
<td>2.85</td>
<td>+0.36/−0.50</td>
</tr>
</tbody>
</table>

Table A3

AMAs for concentric rings using cumulative craters statistics and Poisson statistics represented as PDFs. Distance is to farthest extent of the ring from Aristarchus (e.g. the 125-km-ring includes distances from Aristarchus from just over 100 km to 125 km).

<table>
<thead>
<tr>
<th>Concentric ring</th>
<th>Crater retention age: N(1)</th>
<th>Model age (Ga)</th>
<th>Error (Ga)</th>
<th>Crater retention age, PDF: N(1)</th>
<th>Model Age, PDF (Ga)</th>
<th>Error, PDF (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 km ring</td>
<td>1.65E–02</td>
<td>3.78</td>
<td>+0.06/−0.11</td>
<td>1.09E–02</td>
<td>3.71</td>
<td>+0.13/−0.41</td>
</tr>
<tr>
<td>50 km ring</td>
<td>1.36E–02</td>
<td>3.75</td>
<td>+0.01/−0.01</td>
<td>1.28E–02</td>
<td>3.74</td>
<td>+0.045/−0.044</td>
</tr>
<tr>
<td>75 km ring</td>
<td>6.98E–03</td>
<td>3.61</td>
<td>+0.01/−0.01</td>
<td>6.81E–03</td>
<td>3.60</td>
<td>+0.012/−0.013</td>
</tr>
<tr>
<td>100 km ring</td>
<td>5.08E–03</td>
<td>3.52</td>
<td>+0.01/−0.01</td>
<td>5.26E–03</td>
<td>3.53</td>
<td>+0.0090/−0.0095</td>
</tr>
<tr>
<td>125 km ring</td>
<td>3.60E–03</td>
<td>3.37</td>
<td>+0.02/−0.02</td>
<td>3.81E–03</td>
<td>3.40</td>
<td>+0.015/−0.017</td>
</tr>
<tr>
<td>150 km ring</td>
<td>2.91E–03</td>
<td>3.20</td>
<td>+0.03/−0.04</td>
<td>3.03E–03</td>
<td>3.24</td>
<td>+0.029/−0.035</td>
</tr>
<tr>
<td>175 km ring</td>
<td>2.70E–03</td>
<td>3.09</td>
<td>+0.06/−0.07</td>
<td>2.73E–03</td>
<td>3.11</td>
<td>+0.056/−0.069</td>
</tr>
<tr>
<td>200 km ring</td>
<td>3.12E–03</td>
<td>3.27</td>
<td>+0.03/−0.04</td>
<td>3.24E–03</td>
<td>3.30</td>
<td>+0.029/−0.034</td>
</tr>
<tr>
<td>225 km ring</td>
<td>2.63E–03</td>
<td>3.04</td>
<td>+0.12/−0.18</td>
<td>2.42E–03</td>
<td>2.86</td>
<td>+0.17/−0.21</td>
</tr>
</tbody>
</table>
References


