

Geophysical Research Letters®



RESEARCH LETTER

10.1029/2025GL116654

Key Points:

- Apollo sample 76535 is highly unusual and could have been excavated during the Serenitatis impact event, simplifying its history
- Crater collapse during basin-forming impacts is a pervasive process and deep material is likely to be found in many lunar basins
- Sample 76535 may date the Serenitatis impact event at 4.25 Ga, and this would require a reworking of lunar chronology

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Bjonnes, E., Johnson, B. C., Broquet, A., Garrick-Bethell, I., Andrews-Hanna, J. C., Wakita, S., & Kiefer, W. S. (2025). Evidence for an early formation of Serenitatis Basin at 4.25 Ga shifts lunar chronology. *Geophysical Research Letters*, 52, e2025GL116654. <https://doi.org/10.1029/2025GL116654>

Received 30 APR 2025

Accepted 21 AUG 2025

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Evidence for an Early Formation of Serenitatis Basin at 4.25 Ga Shifts Lunar Chronology

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Abstract Troctolite sample 76535, collected in Serenitatis basin during Apollo 17, formed at least 50 km deep, experienced maximum shock pressures of 6 GPa, and has a ⁴⁰Ar/³⁹Ar excavation age of 4.25 Ga. Previous work attributed 76535 to the South Pole-Aitken (SPA) basin, presumably dating the SPA-impact and constraining lunar bombardment history. Here we use the iSALE-2D shock-physics code and gravity inversion modeling to determine if instead the Serenitatis impact event excavated 76535. We find nearly 140,000 km³ of material (~2% of near-surface ejecta) matching the depth and pressure constraints of 76535 is displaced to the surface during crater collapse of a Serenitatis-like impact event. We conclude that the Serenitatis impact event possibly excavated 76535, redefining its age to 4.25 Ga, 300 My older than the consensus age based on Apollo 17 samples. This finding would provide an important anchor point where lunar chronology where bombardment flux is especially uncertain.

Plain Language Summary During Apollo 17, sample 76535 was collected from the rim of Serenitatis Basin. Studies determined it initially formed near the base of the lunar crust (~50 km depth), leading to questions of how it was brought to the surface. Large impact events can draw material up from the subsurface but reaching 50 km depth requires an extraordinarily large event, akin to the impact that formed the South Pole-Aitken basin. This work considers the possibility that 76535 was brought to the surface instead during the Serenitatis basin impact event, given its proximity at the time of collection. Our work shows that the Serenitatis impact event, and many other large impacts, moved very deep material to the surface during later stages in the crater formation process. Given the prevalence of this process in our work, we conclude that many basins on the Moon likely contain material from similar depths. Furthermore, 76535 is known to be 4.25 billion years old and with our finding that it may have been excavated during the Serenitatis impact, the chronology of lunar basins needs to be reconsidered. Placing the Serenitatis impact at 4.25 Ga necessitates larger basins, such as South Pole-Aitken, to be older than currently estimated.

1. Introduction

Lunar troctolite 76535, collected as a rake sample during Apollo 17 near the southeastern edge of Serenitatis basin, is a puzzling specimen; although its mineral assemblage and petrographic texture indicate it formed deep in the lunar crust, it shows no evidence of high shock pressures (Gooley et al., 1974). Under the traditional model of impact excavation, it is not readily apparent how this sample landed on the lunar surface (Garrick-Bethell et al., 2020).

Serenitatis basin, centered at 25°N 19°E on the lunar nearside, is classified as a multiring basin with a poorly preserved outer Vitruvius ring 740–930 km in diameter, a well-expressed intermediate Haemus ring scarp 610–660 km in diameter, and a possible buried peak ring, indicated by concentric wrinkle ridges, marking the Linné ring 416–420 km in diameter (Neumann et al., 2015; Wilhelms et al., 1987). Although the outermost and innermost topographic rings are incomplete and poorly expressed, a large positive Bouguer anomaly, 490–620 km in diameter clearly indicates a central zone of thinned crust (Neumann et al., 2015). Overlying mare masks crustal thickness and post-impact topography in the interior of Serenitatis. Fortunately, although this mare layer adds complexity to Serenitatis' gravity field, it is possible to constrain its thickness and estimate the initial post-impact

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basin crustal structure using global gravity inversions (Broquet & Andrews-Hanna, 2024) which is integral to estimating Serenitatis' initial basin morphology prior to the emplacement of the mare basalts.

Sample 76535 is compositionally and texturally unique among Apollo-era rocks. Weighing approximately 155 g, it is primarily composed of 58% plagioclase, 37% olivine, and 4% orthopyroxene (Dymek et al., 1975; Gooley et al., 1974). 76535 is therefore a troctolite and, having originated in the mid-to deep-levels in the crust, likely formed as a cumulate (McCallum et al., 2006; McCallum & Schwartz, 2001). Petrographically, the symplectite mineral assemblage of olivine, orthopyroxene, clinopyroxene, Cr-spinel, and plagioclase in the sample indicate equilibrium conditions of $850 \pm 50^\circ\text{C}$ and 220–250 MPa (McCallum & Schwartz, 2001), corresponding to depths of 48–58 km assuming an average crustal thickness of 40 km and density of $2,550 \text{ kg/m}^3$ (Garrick-Bethell et al., 2020; Wiczorek et al., 2013). The sample yields radioisotopic ages of $4,370 \pm 11 \text{ Ma}$ ($^{147}\text{Sm}/^{143}\text{Nd}$), $4,279 \pm 52 \text{ Ma}$ (Rb/Sr), and $4,249 \pm 12 \text{ Ma}$ ($^{40}\text{Ar}/^{39}\text{Ar}$; Borg et al., 2017; Garrick-Bethell et al., 2017). The different ages for the different radiometric systems are related to the unique closure temperatures for each system: $825 \pm 25^\circ\text{C}$ for Sm-Nd, $649 \pm 15^\circ\text{C}$ for Rb-Sr, and $300 \pm 50^\circ\text{C}$ for $^{40}\text{Ar}-^{39}\text{Ar}$ (Borg et al., 2017). These different ages and closure temperatures indicate slow cooling at a rate of $3.9 \pm 1.2^\circ\text{C/Ma}$ (Borg et al., 2017), consistent with the 76535 having originated at deep crustal depths. Fe-Mg disordering in orthopyroxene indicates a cooling rate of 0.04°C/year near a closure temperature of 500°C (McCallum et al., 2006, four orders of magnitude faster than the cooling rate at higher temperatures. This indicates that 76535 was rapidly brought to the surface. The only plausible mechanism for rapidly excavating lunar material from tens of kilometers depth to the surface is a basin-scale impact. Using McCallum et al. (2006)'s cooling rate of 0.04°C/yr , the cooling time from the pyroxene closure temperature of 500°C to the Ar closure temperature of 300°C is just a few thousand years, well within the uncertainty of the $^{40}\text{Ar}-^{39}\text{Ar}$ age. Thus, we accept the conclusion that the 4.25 Ga $^{40}\text{Ar}-^{39}\text{Ar}$ age is the age of the basin-forming impact that exhumed 76535 (Garrick-Bethell et al., 2020). Other workers have recently discussed observations of baddeleyite grains (White et al., 2020) and of chemical heterogeneity in olivine and plagioclase grains (Nelson et al., 2021) that are related to early, rapid cooling from either a magma or an impact melt. These observations of earlier cooling predate the secular cooling discussed here and thus do not contradict our interpretation of the $^{40}\text{Ar}-^{39}\text{Ar}$ age as a basin formation age.

The key question, then, is which basin-forming impact does 76535 date? Notably, 76535 lacks metamorphic features indicating shock pressures above 6 GPa (Garrick-Bethell et al., 2020; Gooley et al., 1974; Nord Jr, 1976) despite being excavated to the surface. Because South Pole-Aitken (SPA) is thought to be the only lunar impact large enough to eject unshocked rocks from such depths (Garrick-Bethell et al., 2020), 76535 may be ejecta dating the SPA impact event. However, after considering ballistic trajectories of SPA ejecta, this necessitates a second impact to deliver it to Serenitatis basin (Garrick-Bethell et al., 2020). Critically, this second impact must also not subject it to shocks higher than 6 GPa which the authors found is physically possible but not highly likely. They also speculated that highly oblique impacts could deliver the rock directly to the nearside. The conclusion that 76535 was initially excavated during the SPA impact is possibly in close alignment with the $^{40}\text{Ar}-^{39}\text{Ar}$ age of 76535 given the recent findings that it may be as recent as $4.247 \pm 0.005 \text{ Ga}$ (Su et al., 2025). Finally, baddeleyite occurrence in some grains suggests that 76535 formed in superheated impact melt $4.328 \pm 0.008 \text{ Ga}$, although White et al. (2020) determined that the impact that generated this melt precedes that which exhumed 76535 and thus is not associated with the excavation event. Although these scenarios may be technically possible, we suggest a simpler history: 76535 was exhumed locally during the Serenitatis impact event during the crater collapse stage, instead of the more conspicuous excavation stage.

76535 offers an opportunity to investigate possible pathways by which initially deep-seated material may find its way to the surface during an impact event. To test if it was advected to the surface during the crater collapse stage of the Serenitatis impact event, we first remove the mare basalt layer infilling Serenitatis basin (Sections 2.1 and 3.1); this step simplifies comparisons between current observations of the basin structure and the hydrocode outputs which do not have a mare component. We then run iSALE models detailing the Serenitatis impact event with a specific focus on matching the distribution of crustal material around Serenitatis basin without the contemporary mare component, similar to previous lunar modeling studies (Miljković et al., 2016; Potter et al., 2012; Sections 2.2 and 3.2). Finally, we consider the broader implications of the Serenitatis impact event occurring at 4.25 Ga, both for lunar chronology and the possibility of the Late Heavy Bombardment (LHB) (Section 4).

2. Methods

2.1. Gravity Inversion Modeling

We developed a crustal thickness inversion method that partitions the crust into a mare top load, a feldspathic top and bottom load, and computes lithospheric displacement as a function of the elastic thickness of the lithosphere (Broquet & Andrews-Hanna, 2024). The pre-mare feldspathic crust and mare relief are obtained from two successive inversions of gravity and topography data. The mare relief is first estimated from a 2-layer constrained inversion where the feldspathic crustal loads are assumed to be Airy compensated at long-wavelengths (degrees < 90) with a smooth transition to flexural support of the mare relief at short-wavelength (degree > 150). This assumption is consistent with the prevailing paradigm that the early crust formed as a floatation crust in a relatively hot Moon early in geologic history (Wood et al., 1970), and where early isostasy of the nearside basins was maintained near the high heat flow PKT region (Wieczorek & Phillips, 1999). The mare thickness is then masked to match the known extent of the lunar maria (e.g. Fortezzo et al., 2020), and negative mare thicknesses are set to zero. The second step inverts gravity and topography for the thickness of the feldspathic crust using the known masked mare thickness. The result is a self-consistent model of mare and crustal thickness matching the expectation for an approximately long-wavelength isostatic pre-mare crust and a flexurally supported mare load.

Following previous studies (e.g. Wieczorek et al., 2013), the mare, crust, and mantle densities were set to 2,850, 2,550, and 3,220 kg m⁻³, finite-amplitude corrections were accounted for when inverting for the crustal thickness, and the crust-mantle interface relief was damped using a minimum amplitude filter with half wavelength 90. The mare relief benefits from the high resolution of GRAIL data and is tapered down from degree 350 to 500. Our nominal model further assumes an elastic thickness of 40 km at the time of mare emplacement (see Broquet & Andrews-Hanna, 2024). The elastic thickness of the lithosphere controls the amount of mare-induced flexure and variations of ± 20 km leads to mare and crustal thickness variations of about 5 km. Variations of ± 150 kg m⁻³ in the density contrast between the mare and feldspathic crust leads to feldspathic crustal thinning variations of ~ 10 km at Serenitatis.

2.2. Hydrocode Modeling

We use the iSALE shock-physics code to simulate impact basin formation under a range of geologic conditions (Amsden et al., 1980; Collins, 2014; Collins et al., 2004; Ivanov et al., 1997; Melosh et al., 1992; Wünnemann et al., 2006). The Collins damage model (Collins et al., 2004) tracks damage relative to brittle-ductile and brittle-plastic transition pressures with an exponential damage dependence (Johnson et al., 2016), leading to increased strain localization in heavily damaged material (Montési & Zuber, 2002). A stress-dependent visco-elastic-plastic rheology model in the mantle captures both short-term and long-term deformation modes (Elbeshausen & Melosh, 2020). A thermal softening model captures the effect of rising temperature on material deformation (Ohnaka, 1995).

As we are simulating large impact basins where the curvature of the Moon is important (Ivanov et al., 2010), we use a curved target geometry with a central gravity field. The mesh is structured with high-resolution regions in both horizontal and vertical direction surrounded by lower-resolution extension zones. Cell size is 1 km in each direction in the high-resolution zone and increases by a factor of 1.03 in the low-resolution zones up, to a maximum cell size of 10 km. The impactor strikes vertically at 12 km/s with a 40, 45, or 50 km radius projectile, resulting in model resolution of 40, 45, or 50 cells per projectile radius. Primary model variables are crustal thickness, lithospheric thermal gradient, and mantle temperature. Although we initially consider two-dimensional geometry and impact melt with negligible viscosity such that any impact melt behaves as a Newtonian fluid, we include three-dimensional models and variable melt viscosities in the Supporting Information S1. The lunar target has a 350 km radius core, 1,350 or 1,355 km thick mantle, and 40 or 35 km thick crust (Wieczorek et al., 2013) such that the total lunar radius is 1,740 km. The surface temperature is 300 K. Thermal conditions are known to affect the material strength of the target during basin-scale impact events (e.g. Bjonnes et al., 2021; Freed et al., 2014; Johnson et al., 2018, 2016); we vary lithospheric thermal gradients between 16 and 30 K/km (Laneuville et al., 2013) and thermal profiles roll over to an adiabatic thermal gradient of 0.06 K/km when the temperature approaches 1,400 K. Crustal material is modeled using strength parameters derived from gabbroic anorthosite (Potter et al., 2012) and a granitic equation of state (Melosh et al., 2013), analogous to previous lunar basin modeling studies (e.g. Bjonnes et al., 2023; Johnson et al., 2018, 2016). Please see the Supporting

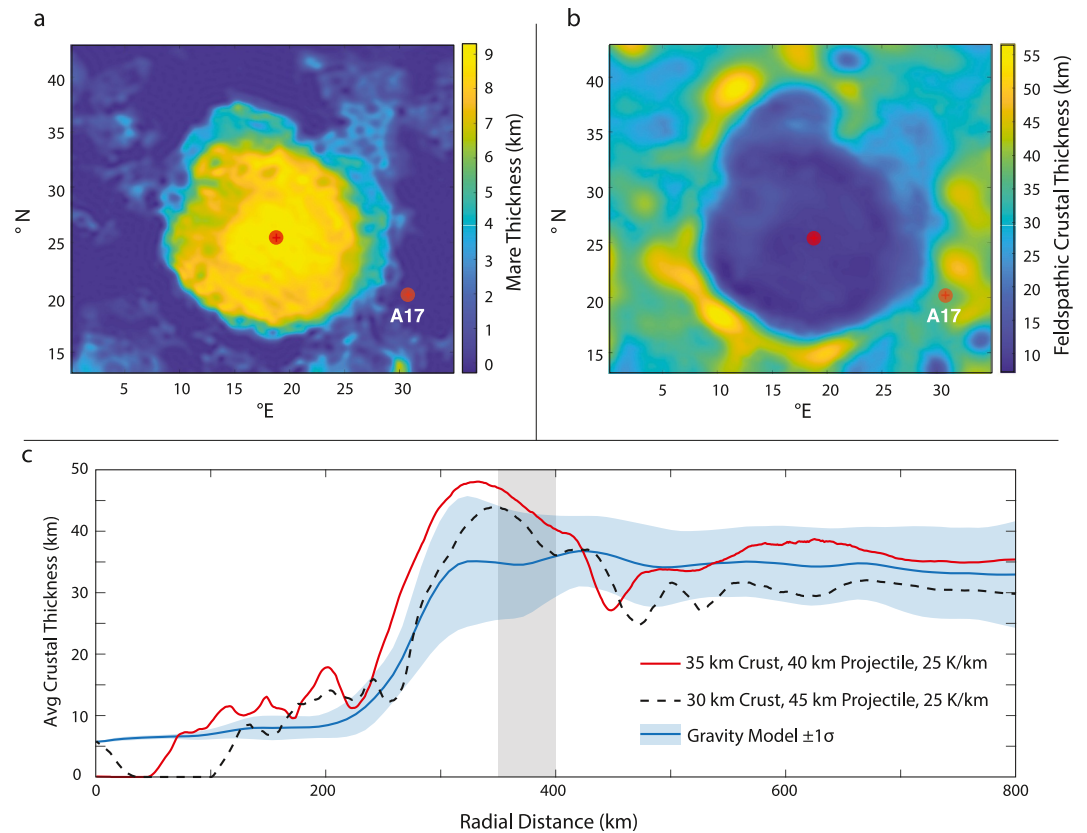


Figure 1. Crustal Thickness Inversion around Serenitatis Basin. Maps of (a) gravity-derived mare thickness, (b) pre-mare crustal thickness, and (c) azimuthally-averaged gravity-derived pre-mare crustal thickness profiles with two example hydrocode crustal thicknesses. The gray bar denotes the approximate radial location of 76535 (350–400 km). The basin center (25.4°N, 18.8°E) and Apollo 17 landing site (20.2°N, 30.8°E) are marked in panels (a, b). Note the effect of Serenitatis North basin on the northwestern flank of Serenitatis in panels (a, b).

Information S1 for physical model inputs (Table S1 in Supporting Information S1) and material parameters (Table S2 in Supporting Information S1).

3. Results

3.1. Crustal Thickness Inversion

Knowing the crustal thickness profile after the Serenitatis impact provides a quantitative constraint for comparison with impact models unaffected by subsequent viscoelastic relaxation and infilling of mare basalts. Determining the crustal structure of mare basins by inverting topography and GRAIL gravity data (Broquet & Andrews-Hanna, 2024) results in thicknesses of the bulk and feldspathic (pre-mare) crust beneath the maria which are substantially different from models neglecting the contribution of the maria. When applying this method to mare Serenitatis (Figure 1), we obtain a mean mare thickness of 9 ± 5 km (Figure 1a), consistent with previous inferences based on surface tectonics (~ 9 km; Solomon & Head, 1980) but higher than estimates using crater morphology (~ 4 km; Williams & Zuber, 1998). However, Williams and Zuber (1998) does not account for the mare-induced flexure of the basin floor, which we estimate to be 4 km. The feldspathic crust is about 6 ± 5 km thick at the center of the basin and is 25–35 km thinner than the surrounding crust (Figures 1b and 1c).

Hydrocode estimates (Section 3.2) of crustal thickness are much more variable, especially within the basin, than the inverted gravity calculations (Figure 1c). This is due to gravity inversion filtering out short-wavelength variations ($< \sim 70$ km) to prevent instabilities and post-impact relaxation smoothing the modern-day crustal structure of the basin. Furthermore, flow toward the basin center after a large impact depends highly on the preimpact thermal conditions and is inherently difficult to model, resulting in iSALE models of basin-forming

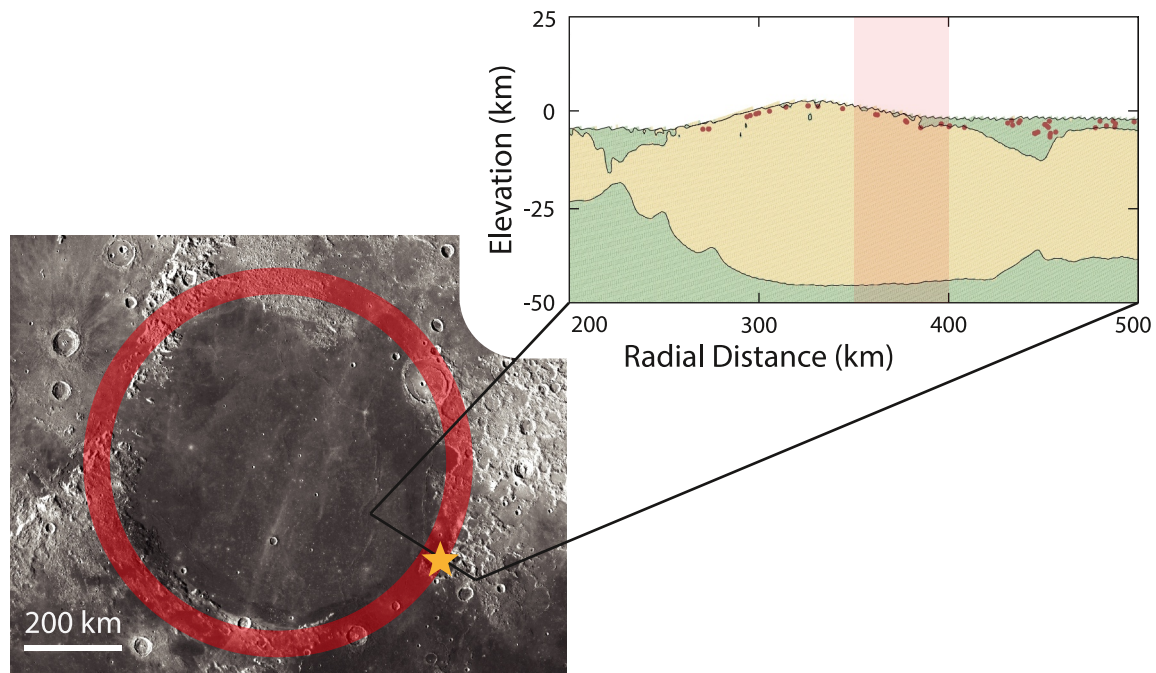


Figure 2. Distribution of 76535-like Material within Serenitatis basin. Regional map of Serenitatis basin collected by Lunar Reconnaissance Orbiter and model result shown. Red circle around Serenitatis matches the approximate distance from basin center where 76535 was collected (350–400 km) and matches the red bar in hydrocode panel. The yellow star denotes the approximate location of Apollo 17. Color denotes granitic crust (brown) and overlying dunite mantle (green). Red particles experience maximum shock pressures of 6 GPa, originated between 45 and 65 km depth, and are within 5 km of the surface at the end of the basin formation.

impacts often showing little to no crustal coverage along the basin floor (Freed et al., 2014; Johnson et al., 2016, 2018). However, we conclude that our models are a good fit based on the $<1\text{-}\sigma$ match between the crustal inversion and iSALE model predictions for much of the radial profile. Within all models tested, hydrocodes with higher thermal gradients match the averaged gravity inversion better but lower thermal gradients replicate the expected crustal bulge seen in discrete regions surrounding Serenitatis (but which is less prominent in the average profile because of the effect of the Serenitatis-North basin; Figure S1 in Supporting Information S1).

3.2. Hydrocode Modeling

Based on post-impact basin dimensions and crustal thickness profiles, we find that a Serenitatis-like basin forms when a 40-km radius projectile strikes a Moon-like target with 35-km thick crust and 25-K/km thermal gradient. Producing a zone of thinned crust ~ 600 km in diameter, in agreement with the observed Bouguer anomaly (Neumann et al., 2015). This modeled basin has crustal thickness maxima at approximately 200 and 325 km radius (Figure 1), roughly corresponding to the Linné (210 km) and Haemus (330 km) topographic rings of Serenitatis. However, later processes such as viscous relaxation and isostatic adjustment are not accounted for in this model, which leads us to instead compare the post-impact crustal thickness profile with that of the modern-day basin (e.g. Freed et al., 2014; Melosh et al., 2013; Trowbridge et al., 2020). The dynamics of basin formation shown here are in agreement with previous studies of lunar basin formation (e.g. Johnson et al., 2018, 2016; Miljković et al., 2017; Freed et al., 2014; Figure S2 in Supporting Information S1). After approximately 2 hr, the basin's final morphology is formed (Figure 2), with $140,000 \text{ km}^3$ of material with original depth between 45 and 65 km and maximum shock pressure of 6 GPa within 5 km of the surface, analogous to 76535. At a radial distance of 350–400 km, approximately where 76535 was collected, material like 76535 comprises 1.76% of material within 5 km of the surface in our models, consistent with proportion of olivine-rich material detected around several nearside basins, including Serenitatis (Yamamoto et al., 2010).

We tested lithospheric thermal gradients between 16 and 30 K/km and mantle rollover temperatures of 1,300–1,500 K. Although we focused on the formation of Serenitatis, initially deep-seated material from the lower crust and upper mantle was drawn up to the surface with low shock pressures in all models with mantle temperatures of 1,400 or 1,500 K, and some models with a mantle temperature of 1,300 K (Figure S3 in Supporting

Information S1), in accordance with previous modeling work (Johnson et al., 2016) and remote sensing observations (Cheek et al., 2013). Furthermore, a three-dimensional test of our baseline Serenitatis model verified that model geometry is not affecting our conclusions (Figure S4 in Supporting Information S1). Finally, given that melt viscosity affects material transport during an impact, we tested a range of impact melt viscosities between 10^5 and 10^{10} Pa s to complement our initial models with a melt viscosity of 0 Pa s. Melt viscosities up to 10^8 Pa s do not change our conclusions but viscosities of 10^9 – 10^{10} Pa s suppress upward mobility and prevent material like 76535 from advecting to the surface (Figures S5 and S6 in Supporting Information S1). Consequently, this hypothesis can accommodate a component of lithic clasts within the impact melt, thus increasing its effective viscosity, while maintaining consistency with observations. The percentage of 76535-like material is approximately 2% for mantle viscosities up to 10^7 Pa s, after which it drops to 1% for a viscosity of 10^8 Pa s and is 0% for models with viscosities of 10^9 Pa s or above. If considering material distributed 350–400 km from the basin center, the relative occurrence of 76535-like material peaks at ~5% for a mantle viscosity of 10^5 Pa s but otherwise shows similar trends compared to material distributed across the model domain (Figure S6 in Supporting Information S1). Interestingly, the highest relative amount of 76535-like material between 350 and 400 km radius (~5%) is predicted for a mantle viscosity of 10^5 Pa s, but the general abundance of 76535-like material hovers at approximately 2%, in accordance with only one sample having been collected during Apollo 17.

We find the 25 K/km model to be the best fit considering the match between crustal thickness profiles and the location of maximum crustal thickness, approximately 300 km from the point of impact. Although this thermal gradient is higher than the range of 8–17 K/km inferred from petrological constraints (e.g., Figure 21 of Garrick-Bethell et al., 2020), higher temperatures serve to primarily weaken material, facilitating more intense collapse of the transient crater and subsequent basin modification. Similar effects can be achieved via transient weakening mechanisms such as the Melosh model of acoustic fluidization (Rajšić et al., 2024), fault weakening (Senft & Stewart, 2009), or Brittle Damage with Local thermal softening (BDL) (Crawford & Schultz, 2015) models. Our models do not include a transient weakening model and thus, may overestimate the thermal conditions needed to replicate basin characteristics.

4. Discussion

The displacement of 76535-like material to the lunar surface under a range of pre-impact parameters suggests the process of transporting initially-deep material to the surface during crater collapse is pervasive. In a narrower view, this connects the 4.25 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ date preserved in 76535 to the Serenitatis impact event. Although Serenitatis' age has been estimated between 3.9 Ga (Wilhelms et al., 1987) and 3.85 Ga (Evans et al., 2018), there are several lines of evidence that it is older than 3.9 Ga. N(20) crater counts within Serenitatis support an older age with a technique that, by focusing on craters larger than 20 km diameter, is less likely to be distorted by secondary crater effects (Fassett et al., 2012). Orgel et al. (2018) pushes back the age of all lunar impacts by an average of 24%, concluding that Serenitatis formed at 4.22 ± 0.03 Ga, using a technique considering landscape obliteration from large impacts when calculating the densities of smaller craters, increasing the influence of these smaller, more frequent, impacts. However, small sample size, poor preservation, and the obscuring effect of Imbrium's ejecta complicate dating Serenitatis via crater counting.

We also compare our results to radioisotopic ages reported from the Apollo 17 site. In particular, the mean 3.893 ± 0.009 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ age (Steiger & Jäger, 1977) (uncorrected for modern constants) of Apollo 17 impact melts (Dalrymple & Ryder, 1996; Stöffler et al., 2006) suggest that the Apollo 17 impact melt breccias from the North and South Massifs actually date the Imbrium basin ejecta expected to blanket the site (Haskin et al., 1998; Spudis et al., 2011). An Imbrium component of some Apollo 17 samples is supported by 3.92-Ga-age zircons in Apollo 17 impact melt breccias that are geochemically similar to Imbrium ejecta (Zhang et al., 2019), a possibility also suggested by Schaeffer and Schaeffer (1977). As for samples older than ~4.0 Ga at the Apollo 17 site, they are rare. Notably, norite breccia 78155 has a well-defined $^{40}\text{Ar}/^{39}\text{Ar}$ age of 4.195 ± 0.037 Ga (1σ), similar to the value reported by Turner and Cadogan (1975) after decay constant correction. Samples 78235 and 78236 recovered from a norite boulder show evidence for a shock event at $4.188 \text{ Ga} \pm 0.013 \text{ Ga}$ ($^{40}\text{Ar}/^{39}\text{Ar}$, 1σ) (Fernandes et al., 2013) or 4.210 ± 0.014 Ga (U/Pb, 2σ) (Černok et al., 2021), both of which are similar to earlier reported $^{40}\text{Ar}/^{39}\text{Ar}$ ages for 78235/6 (Aeschlimann et al., 1982; Nyquist et al., 1981). These shock events are inferred by Černok et al. (2021) to date the Serenitatis impact at ~4.2 Ga. However, 78235 and 78236 show extensive complicating shock features and shocked grains in 78235 show discordant ^{40}Ar - ^{39}Ar ages compared to

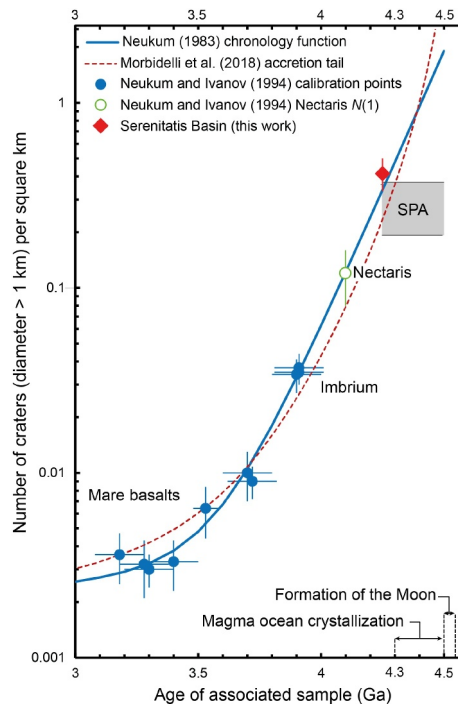


Figure 3. Modified Lunar Chronology. Lunar chronology with 4.25 Ga age for Serenitatis, modified from Garrick-Bethell et al. (2020). Red diamond shows the current $^{40}\text{Ar}/^{39}\text{Ar}$ age of 76535 (4.25 ± 0.01 Ga) and N(1) ($4.2 \pm 0.8 \times 10^{-1}$ km $^{-2}$) estimate for the Serenitatis basin. Gray box shows the uncertainty in SPA N(1) based on values reported in Garrick-Bethell et al. (2020, upper) and Fassett et al. (2012, lower) (converted from N(20) via $N(1) = 1400N(20)$ (Marchi et al., 2012; Morbidelli et al., 2012); but see also the crater production functions of Neukum (1983, 2001), and Liu et al. (2023) for alternative N(1)/N(20) values). For more detail see Garrick-Bethell et al. (2020).

radioisotopic ages recorded in the sample's phosphate grains. Furthermore, the ~ 4.2 Ga ages of 78235/6 (Černok et al., 2021; Fernandes et al., 2013) are nonoverlapping with the well-defined 4.249 ± 0.012 Ga (1σ) $^{40}\text{Ar}/^{39}\text{Ar}$ excavation age of 76535 (Garrick-Bethell et al., 2017) within two-standard deviation uncertainties, and 78155's ~ 4.2 Ga age is nonoverlapping at the 1-standard deviation level, suggesting they are unrelated to the event that excavated 76535. Because 76535 can be linked to Serenitatis through its unique shock history and depth of origin, it provides the most reliable estimate of Serenitatis's age.

If the age of Serenitatis is 4.25 Ga, it compels a reworking of lunar chronology, including the age of the South Pole-Aitken basin impact and the plausibility of the LHB, a postulated period between 3.5 and 4.1 Ga defined by an increase in inner solar system impacts (Bottke & Norman, 2017). Several basins are presumed to be older than Serenitatis based on crater counting, with SPA being the oldest (Wilhelms et al., 1987). If 76535 dates Serenitatis, a Pre-Nectarian basin, this implies other Pre-Nectarian basins—including SPA—are also older. Currently, crater-statistics age estimates exist for Imbrium, Nectaris, Crisium, and Serenitatis (Fischer-Gödde & Becker, 2012; Lawrence et al., 2003; Warren, 2003; Wilhelms et al., 1987) and of these, only Imbrium is certain. Four studies have estimated the relative age of SPA from the statistics of small craters superimposed on its surface (Figure 3; Fassett et al., 2012; Garrick-Bethell et al., 2020; Marchi et al., 2012; Orgel et al., 2018), and the discrepancies between estimated ages of SPA and the nearside basins underscore the uncertainty in relative ages of the basins as well as the crater formation rate at the time of SPA formation, upon which much of lunar chronology is based. That our work aligns with other studies dating Serenitatis to approximately 4.25 Ga urges a reconsideration of lunar basin chronology, likely resulting in older age estimates for nearside basins. Recent work constraining the age of SPA has resulted in ages from 4.25 Ga (Su et al., 2025) up to 4.33 Ga (Joy et al., 2025). A gap between the SPA and nearside basin impacts would support the theory of a LHB whereas similar ages of SPA and other basins would indicate a monotonically

declining rate of bombardment; clearly, accurately determining the time elapsed between the SPA impact and those of the nearside basins—including Serenitatis—is critical for determining the likelihood of the LHB.

5. Conclusion

We find that 76535 was possibly displaced to the lunar surface during the crater collapse stage of the Serenitatis impact. Interestingly, similarly-deep material is brought to the surface under a variety of preimpact conditions, suggesting that this is a pervasive part of the basin formation process. If 76535 was excavated during the Serenitatis impact, a reconsideration of lunar chronology is needed to better understand the impact history on the Moon. Sample 76535 has previously been attributed to the SPA impact and inferred to date that event but, if its 4.25 Ga age is instead tied to the Serenitatis impact, several nearside lunar basins will be older than previously thought and lunar chronology stretches farther back in time.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

iSALE is not currently available to the public and is accessible to the impact community on a case-by-case basis for non-commercial use. Scientists interested in using or developing iSALE can reference <https://isale-code.github.io> for a description and application requirements. Model input files and outputs are available on the

Harvard Dataverse (Bjornnes, 2024). The global crust and mare thickness model data can be found at Broquet and Andrews-Hanna (2024). The crustal and mare thickness inversion code is available at Broquet (2022).

Acknowledgments

The authors thank the developers of iSALE-2D and pySALEplot, including Gareth Collins, Kai Wünnemann, Dirk Elbeshausen, Tom Davison, Boris Ivanov, and Jay Melosh, without whom this work would not be possible. We also thank Taylor Bourikas for her help with initial model analysis. This work was supported by NASA Cooperative Agreement 80NSSC20M0173, NASA Lunar Data Analysis Program Grant 80NSSC21K0048, and NASA SSERVI Grant 80NSSC23M0161. We also gratefully acknowledge the developers of iSALE-3D, including Dirk Elbeshausen, Kai Wünnemann, and Gareth Collins. Numerical computations of iSALE-3D were carried out on Small Parallel Computers at Center for Computational Astrophysics, National Astronomical Observatory of Japan. Portions of this work were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Lab under contract DE-AC52-07NA27344. LLNL-JNL-864574.

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