TAKING A CLOSE LOOK AT DATING OLD IMPACT MELT ROCKS: HIGH SPATIAL RESOLUTION ^{40}Ar/^{39}Ar GEOCHRONOLOGY OF SOME APOLLO 17 SAMPLES.

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Introduction: Geochronologic studies of lunar rocks have provided fundamental insights into the formation and evolution of the Moon by both endogenic and exogenic processes [e.g., 1–3]. Importantly, recent and ongoing geochronologic studies of Apollo samples are continuing to shed new light on longstanding problems in lunar geology, such as the timing of major basin-forming impacts and the nature of the putative lunar cataclysm [e.g., 4–6]. During their mission to the Taurus-Littrow Valley in December 1972, the Apollo 17 astronauts collected samples from several major physiographic units, which were influenced by multiple basin-forming impacts (e.g., Crisium, Serenitatis, and Imbrium), effusive and pyroclastic volcanism, tectonism, and impact gardening [7]. These samples continue to provide a wealth of new information more than four decades after their collection [e.g., 8].

A variety of mineral isotopic systems have been used to date impact melt rocks (IMRs) recovered from the Apollo landing sites, such as U/Pb in zircons and phosphates, Pb/Pb, Sm/Nd, and Rb/Sr internal isochrons, and ^{40}Ar/^{39}Ar incremental heating experiments [e.g., 2, 4, 5, 9–14]. In many cases [e.g., 2, 5, 10–14] these dates have been interpreted as the ages of specific basin-forming impacts (e.g., Crisium, Serenitatis, Imbrium). Recently, significant emphasis has been placed on relatively few U/Pb dates, even though most available impact dates are arguably based on ^{40}Ar/^{39}Ar datasets. Unfortunately, reaching a consensus on the ages of major lunar impact basins has been elusive, and remains a challenge for the planetary science community. One complication is that many lunar samples experience multiple impact events [e.g., 10, 14, 16]. Because the diffusivities of daughter elements differ among various mineral-isotopic systems (e.g., Pb diffusion is slower in zircon than Ar diffusion is in feldspars), the susceptibility of each system to impact resetting also differs, making it difficult to robustly attribute any individual date determined by a single technique to a specific basin-forming impact.

A combination of petrologic and geochronologic investigations at both bulk- and micro-scales can help to more fully understand samples with complex impact histories. We have used the ultraviolet laser ablation microprobe (UVLAMP) ^{40}Ar/^{39}Ar method to date six Apollo 17 IMRs (72255, 73217, 76315, 77075, 77115, and 77135) at high spatial resolution [16–18]. Our work reinforces that while some IMRs are monogenetic, others appear to be polygenetic, and some samples have experienced significant post-formation thermal disturbances that place limited constraints on the actual ages of impact melting events. By directly dating petrographically distinctive impact melt and clast domains within individual samples, the UVLAMP ^{40}Ar/^{39}Ar method can be used to effectively unravel the impact histories of texturally complex and/or polygenetic IMRs, and both complements and expands upon incremental heating ^{40}Ar/^{39}Ar datasets.

The UVLAMP ^{40}Ar/^{39}Ar Method: The UVLAMP ^{40}Ar/^{39}Ar technique [19] uses a pulsed UV (e.g., λ = 193 nm) laser to extract Ar gasses from neutron irradiated samples for isotopic analysis by a noble gas mass spectrometer. UV lasers have two major advantages over visible and infrared (IR) lasers: (1) UV lasers couple well with most geological materials, including phases that are mostly transparent at visible and IR wavelengths (like some feldspars and glasses); and (2) UV lasers with short pulse durations (e.g., 5 ns) cause very little collateral heating, so there is no measurable release of Ar gasses from phases outside of individual ablation pits [16, 20, 21]. All age uncertainties are reported at 2σ, and we used the decay constants of Steiger and Jäger [22]. See Mercer et al. [16] for additional details on our analytical methods.

Results and Discussion: UVLAMP ^{40}Ar/^{39}Ar data for melt in samples 72255, 76315, and 77115 indicate that these IMRs each contain a single generation of impact melt, and inherited mineral and lithic clasts are generally the same age or older than their host melts. Even small plagioclase clasts that are only a few hundreds of microns in diameter can be distinctly older then their host melts (e.g., on the order of 100’s of Ma older). Our UVLAMP date of 3834 ± 20 Ma [16] for melt in 77115 is indistinguishable from two of the three ^{40}Ar/^{39}Ar plateau dates reported by Stettler et al. [23, 24]. Preliminary UVLAMP dates for the melt components of 72255 and 76315 are slightly (~50–80 Ma) younger than published plateau dates [10, 12, 25], possibly because we were able to separately analyze melt components and inherited clasts.

Sample 73217 is a complex rock with multiple petrographically and chemically distinct breccia components [16 and references therein, 26]. Grange et al. [13] reported U/Pb dates for phosphates and zircons that they interpreted as evidence for two impact events at 4335 ± 5 Ma and 3934 ± 12 Ma. We reported UVLAMP ^{40}Ar/^{39}Ar data for three breccia lithologies in 73217 that we interpreted as evidence for at least three additional impact melt-forming events that occurred between ca. 3810 Ma and at least as young as ca. 3270 Ma [16]. UVLAMP dates of small plagioclase clasts in 73217 indicate they are older than their host melts. Thermal-kinetic modeling supports the possibility that polygenetic IMRs can retain evidence for multiple melt-forming impacts, particularly if the melt generations contain clasts [27]. If such samples are identified during future sampling missions, they should be regarded as potentially high-value targets.

While published plateau dates seem to indicate that 77075 is older than 77115 [23, 24, 28], our UVLAMP data imply that 77075 experienced partial ^{40}Ar* loss, providing a minimum age of ca. 3760 Ma and allowing for the possibility that 77075 may have indeed formed contemporaneously with 77115 as suggested by field observations [7, 26, 28]. UVLAMP ^{40}Ar/^{39}Ar dates for 77135 are highly dispersed, consistent with incremental heating ^{40}Ar/^{39}Ar datasets that indicate the sample experienced partial ^{40}Ar* loss [12, 23, 24, 28]. Our work reveals previously unrecognized complexities in the ^{40}Ar/^{39}Ar systematics of plagioclase clasts in 77135. A large (mm-scale) plagioclase clast fragment partly preserves an ^{40}Ar diffusive loss profile, which may be useful in constraining the thermal history of the impact melt deposit in which 77135 formed. Additionally, some small (e.g., 150–300 µm diameter) plagioclase clasts in 77135 appear to be younger than the oldest melt components, while other similarly sized clasts are distinctly older than the melt. Because we left at least several microns of margin outside of clast ablation pits, we consider ^{39}Ar recoil to be an unlikely mechanism to have produced the young dates of some small clasts. Alternatives include the presence of subgrain fast-diffusion pathways, and ^{40}Ar* loss above the kinetic crossovers among the diffusivities of Ar in different phases. These observations provide direct insights into interpreting how various phases release gasses during step heating ^{40}Ar/^{39}Ar experiments.

Conclusions: Despite the many complexities of lunar IMRs (e.g., the presence of small, old clasts, post-formation ^{40}Ar* loss, and polygenetic samples, etc.), the UVLAMP ^{40}Ar/^{39}Ar and incremental heating ^{40}Ar/^{39}Ar methods provide important constraints on the ages of some of the impact meltings events recorded by rocks in the Apollo 17 collection. These results augment U/Pb results, and should not be misinterpreted as somehow less accurate than the U/Pb results. Rather, lunar rocks that have data produced from multiple radioisotopic dating methods should be treated as thermochronologic systems with prolonged, potentially complicated thermal histories. At present, we feel that all of the published datasets (including both U/Pb and ^{40}Ar/^{39}Ar) do not provide unambiguous constraints on the precise and accurate ages of any specific basin-forming impact. A better understanding of the chronology of major basin-forming impacts will likely require a much more systematic study of a larger number of samples, both from existing collections and from sample sets brought back by future missions. Such efforts should integrate petrologic and multiple chronometric methods at bulk-sample and microscales.

The extreme intra- and inter-sample variability of geochronologic results from the Apollo 17 sample suite (and other Apollo sample collections) argues against relying on the results for a small sample set to make large-scale inferences. This observation should help guide design strategies for future missions aimed at establishing a better chronological framework for the geological evolution of the Moon.

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