EARLY IMPACTS ON THE MOON: CRYSTALLIZATION AGES OF APOLLO 16 MELT BRECCIAS.

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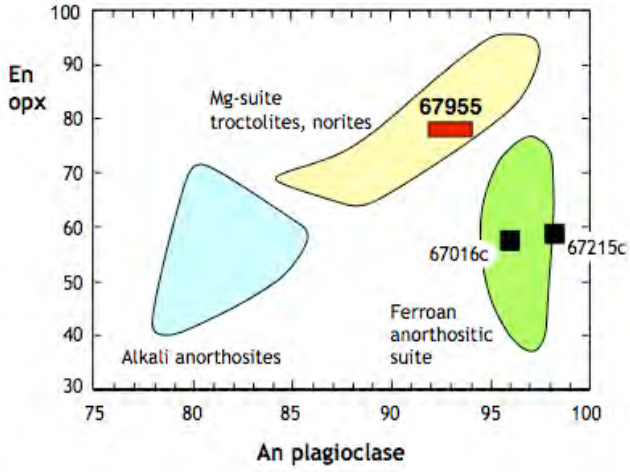
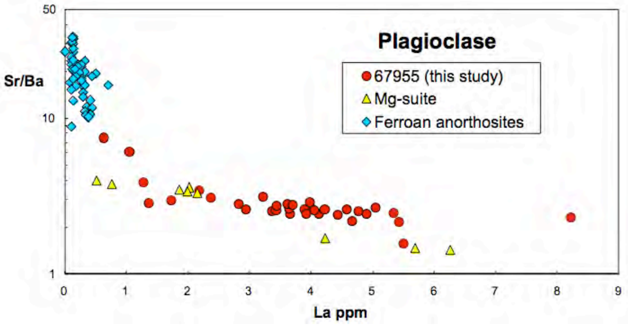
Introduction: A better understanding of the early impact history of the terrestrial planets has been identified as one of the highest-priority science goals for solar system exploration. Crystallization ages of impact melt breccias from the Apollo 16 site in the central-nearside lunar highlands show a pronounced clustering of ages from 3.75-3.95 Ga, with several impact events being recognized by the association of textural groups and distinct ages [1]. Here we present new geochemical and petrologic data for Apollo 16 crystalline breccia 67955 that document a much older impact event with an age of 4.2 Ga.

Petrography: 67955 is a crystalline anorthositic norite breccia collected from the rim of North Ray crater. It has a poikilitic texture with euhedral-subhedral crystals of plagioclase and olivine surrounded by pyroxene oikiocrysts. FeNi metal, phosphate, ilmenite, and chromite are present as minor phases, with metal and phosphate typically in contact. The rock has been brecciated and is cut by veins of dark glass [2,3]. We concur with earlier interpretations that 67955 crystallized from a high-temperature melt [2, 3]. Fe-Ni-Co and PGE compositions of the metal indicate meteoritic contamination of the melt. The texture and bulk composition of 67955 is most directly interpreted as that of a slowly cooled impact-melt rock that was brecciated and veined in a later event.

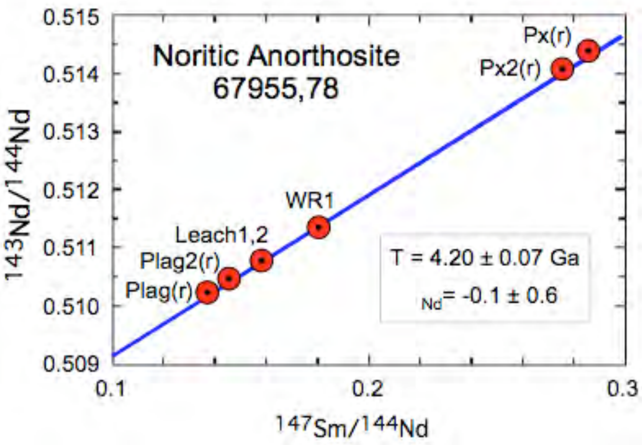
Mineral compositions: Major-element and trace-element compositions of minerals in 67955 demonstrate the predominance of Mg-suite components in this rock. An vs. En compositions of coexisting plagioclase and low-Ca pyroxene plot well within the field for Mg-suite norite and troctolites (Fig. 1).



Plagioclase grains in 67955 have low Sr/Ba ratios similar to those of Mg-suite rocks (Fig. 2). A minor component with Sr/Ba ratios trending toward lunar ferroan anorthosite may be present (Fig. 2). Lindstrom and Lindstrom [4] noted a close correspondence between the whole-rock trace element composition of 67955 and Mg-suite norites and troctolites.



Radiogenic isotopes: ^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, ^{87}Rb-^{86}Sr, and ^{40}Ar-^{39}Ar isotopic compositions were measured on mineral separates and whole-rock samples taken from a well-preserved crystalline area of the rock. ^{147}Sm/^{144}Nd vs. ^{143}Nd/^{144}Nd isotopic compositions of plagioclase, pyroxene, and whole-rock splits form a linear array corresponding to an age of 4.20 ± 0.07 Ga (Fig. 3). A younger (~3.8 Ga) disturbance appears to be present in the plagioclase fraction, and an older age of 4.34 ± 0.03 Ga can be calculated from the pyroxene and whole-rock data. The ^{142}Nd data are consistent with a T_{LEW} model age of ≤4.3 Ga.



The Rb-Sr isotope data are complex. An age of 4.14 ± 0.25 Ga can be calculated from the whole rock, a leached plagioclase (PLAG1r), and a leached pyroxene (PX1r) sample, which is within error of the ^{143}Nd isochron age (Fig. 3). However, two other splits of leached plagioclase (PLAG2r) and pyroxene (PX2r) and the leachates indicate a younger disturbance with a nominal age of ~900 Ma. The ^{40}Ar-^{39}Ar compositions have been highly disturbed by a very young, essentially zero-age diffusive loss of ^{40}Ar. The minimum age obtained from the high-T extractions is ~3.7 Ga although no plateau was observed.

Discussion: The ^{147}Sm-^{143}Nd isotopic data are most directly interpreted as the crystalline age of 67955. Following our interpretation of 67955 as an impact-melt breccia, this would provide the date of a specific impact event into the lunar feldspathic crust at 4.2 Ga. This is the first discrete breccia-forming impact event demonstrably older than 4.0 Ga that has been recognized from the Apollo collection. This impact was probably a sizable event, as indicated by the slowly cooled texture of 67955 (referred to as 'plutonic' in earlier descriptions [2, 3]), although we have not attempted to estimate the size of the parent crater.

Major- and trace-element compositions of mineral and whole-rock samples of 67955 demonstrate the predominance of Mg-suite rocks in the target lithologies melted by this impact event. Low Sr/Ba ratios in the plagioclase may also reflect a KREEP signature, which was likely present as a chemical component in the Mg-suite target rocks. If Korotev's [5] suggestion that the association of Mg-suite cumulates and KREEP is restricted to the Procellarum terrane is correct, then 67955 may have formed some distance from the Apollo 16 site where it was collected. The ~900 Ma event suggested by the Rb-Sr isotope data raises the possibility of ejection by Copernicus [6], which would be consistent with a source in the Procellarum terrane. However, 67955 also represents a magnesian compositional endmember for the Descartes feldspathic fragmental breccias [7] so a more local immediate provenance may be preferred.

Testing the cataclysm hypothesis with new lunar missions: New manned and robotic missions to the Moon over the coming decades will provide exciting opportunities for returning suites of lunar samples from previously unexplored terranes, and for conducting *in-situ* experiments that will better define the impact history of the Earth and Moon. Resolving the question of whether or not an intense bombardment of incoming planetesimals struck the Earth and Moon during a relatively brief episode at ~3.9 Ga is important for understanding the potential significance of large impact events on crustal and biologic evolution, establishing absolute timescales of geological events on other planets, and understanding planetary dynamics in the Solar System.

Where to go on the Moon to obtain a clear test of the cataclysm hypothesis should be an important consideration for science goals during the next phase of lunar exploration. The South Pole-Aitken basin (SPA) provides an attractive exploration target for many reasons, but the age of SPA may not necessarily provide a definitive test of the cataclysm hypothesis. SPA is stratigraphically the oldest basin on the Moon [8]. From its well-preserved structure, pristine relief, and lack of viscous relaxation [9] it must have formed on relatively strong and cool lithosphere. Recent data for the short-lived ^{182}Hf-^{182}W isotope system, however, suggest that formation and internal differentiation of the Moon may have been very fast, within 30-50 million years of initiation of the solar nebula [10]. In this case, the lunar crust may have been capable of supporting large impact structures within 10^8 years [11], especially in regions depleted in heat-producing elements such as the KREEP-poor region around SPA. In this scenario, SPA could be as old as 4.4 Ga. whereas a young age for SPA (e.g. 4.0 Ga) would prove the cataclysm hypothesis, an old age of SPA (e.g. 4.4 Ga) would not provide a definitive test.

In contrast, the age of a stratigraphically younger basin such as Nectaris may provide a more diagnostic test of the cataclysm. Nectaris is one of the oldest nearside basins and together with Imbrium stratigraphically brackets 12 lunar basins [6, 8]. The age of Nectaris is often quoted as 3.92 Ga [6], but in fact, its age remains highly uncertain. The Descartes Formation, sampled by North Ray crater breccias at the Apollo 16 site, has been considered to be a prime candidate for Nectaris ejecta [6]. However, ^{40}Ar-^{39}Ar ages of anorthositic clasts from Descartes breccia 67016 (3.86 $\pm$ 0.01 Ga) [12] are identical to the commonly accepted age for Imbrium (3.85 $\pm$ 0.02 Ga) [6], and the presence of KREEPy and Mg-suite components in some of these breccias [13; this study] suggests that emplacement of the Descartes breccias as Imbrium deposits may be more likely versus an origin as Nectaris ejecta.

Determining a reliable age for Nectaris may provide a definitive test of the cataclysm hypothesis regardless of the outcome. For example, an age of 4.2 Ga for Nectaris would flatten the lunar cratering curve significantly and would effectively disprove the cataclysm hypothesis. On the other hand, if an age of 3.9 Ga could be confirmed for Nectaris, this would provide definitive proof that a cataclysmic bombardment struck the Earth and Moon during a relatively brief episode of intense cratering.

Conclusions: Our new age determination of 4.2 Ga for crystalline impact-melt breccia 67955 based on a ^{147}Sm-^{143}Nd mineral isochron shows that earlier discussions of the lunar impact record emphasizing the lack of events significantly older than 3.9 Ga [6] may need to be revised [14]. However, Turner [15] presented statistical arguments that a genuine gap in lunar impact ages between 4.2 and 3.9 Ga would constitute strong evidence favoring a spike in the cratering rate at 3.9 Ga. Obviously with only one documented lunar impact event at 4.2 Ga, the record is sparse and far from complete. We have, however, demonstrated that it is possible to lift the veil of the 3.9 Ga overprint and begin to unravel the earlier impact history of the Moon.

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