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Diverse impactors in Apollo 15 and 16 impact melt rocks: Evidence from osmium isotopes and highly siderophile elements

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Abstract

Concentrations of highly siderophile elements (HSE) and $^{187}Os/^{188}Os$ isotopic compositions for eleven impact related rocks from the Apollo 15 and 16 landing sites are reported and combined with existing geochronological data to investigate the chemical nature and temporal changes in the large impactors implicated in the formation of the lunar basins. Data for the samples all define linear trends on plots of HSE versus Ir concentrations, whose slopes likely reflect the relative HSE compositions of the dominant impactors that formed the rocks.

The inferred Imbrium basin impactor that generated Apollo 15 impact melt rocks 15445 and 15455 was characterized by modestly suprachondritic $^{187}Os/^{188}Os$, Ru/Ir, Pt/Ir and Pd/Ir ratios. Diverse impactor components are revealed in the Apollo 16 impact melt rocks. The $^{187}Os/^{188}Os$ and HSE/Ir ratios of the impactor components in melt rocks 60635, 63595 and 68416, with reported ages <3.84 Ga, are within the range of chondritic meteorites, but slightly higher than ratios characterizing previously studied granulitic impactites with reported ages >4.0 Ga. By contrast, the impactor components in melt rocks 60235, 62295 and 67095, with reported ages of ∼3.9 Ga, are characterized by suprachondritic $^{187}Os/^{188}Os$ and HSE/Ir ratios similar to the Apollo 15 impact melt rocks, and may also sample the Imbrium impactor. Three lithic clasts from regolith breccias 60016 and 65095, also with ∼3.9 Ga ages, contain multiple impactor components, of which the dominant composition is considerably more suprachondritic than those implicated for Imbrium and Serenitatis (Apollo 17) impactors. The dominant composition recorded in these rocks was most likely inherited from a pre-Imbrium impactor. Consideration of composition versus age relations among lunar impact melt rocks reveals no discernable trend.

Virtually all lunar impact melt rocks sampled by the Apollo missions, as well as meteorites, are characterized by $^{187}Os/^{188}Os$ and HSE/Ir ratios that, when collectively plotted, define linear trends ranging from chondritic to fractionated compositions. The impact melt rocks with HSE signatures within the range of chondritic meteorites are interpreted to have been derived from impactors that had HSE compositions similar to known chondrite groups. By contrast, the impact melt rocks with non-chondritic relative HSE concentrations could not have been made by mixing of known chondritic impactors. These signatures may instead reflect contributions from early solar system bodies with bulk chemical compositions that have

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not yet been sampled by primitive meteorites present in our collections. Alternately, they may reflect the preferential incorporation of evolved metal separated from a fractionated planetesimal core.

Pre-4.0 Ga ages for at least some impactor components with both chondritic and fractionated HSE raise the possibility that the bulk of the HSE were added to the lunar crust prior to the later-stage basin-forming impacts, such as Imbrium and Serenitatis, as proposed by Fischer-Gödde and Becker (2012). For this scenario, the later-stage basin-forming impacts were more important with respect to mixing prior impactor components into melt rocks, rather than contributing much to the HSE budgets of the rocks themselves.

1. INTRODUCTION

The Moon provides a record of the end stages of major planetary accretion to the inner solar system in the form of large impact basins. The observed basin-forming impacts have been interpreted by some to be a result of a putative late heavy bombardment of the inner solar system that occurred between approximately 4.1 and 3.8 billion years ago (Tera et al., 1974; Ryder, 2002; Norman et al., 2006). However, the timing and source of the impactors have been controversial. Regardless of timing, the basin-forming impact events generated voluminous impact melt rocks and breccias that are typically enriched, relative to pristine lunar crustal rocks, in impactor-derived highly siderophile elements (HSE: here including Re, Os, Ir, Ru, Pt, and Pd) (e.g., Anders et al., 1973; Morgan et al., 1974; Higuchi and Morgan, 1975; Wasson et al., 1975; Gros et al., 1976; Hertogen et al., 1977; Korotev, 1987, 1994; Norman et al., 2002; Puchtel et al., 2008; Fischer-Gödde and Becker, 2012; Sharp et al., 2014). Consequently, impact melt rocks can provide important information about the relative concentrations of the HSE present in impactors involved in basin-forming events on the Moon, and by inference, contemporaneous impacts occurring on the Earth and other terrestrial planets.

Studies of Apollo and meteoritic lunar impact melt rocks have reported that, whereas some have HSE characteristics that are well within the range of chondritic meteorites, others are characterized by suprachondritic $^{187}Os/^{188}Os$ (a proxy for long-term Re/Os evolution), Ru/Ir, Pt/Ir, Au/Ir and Pd/Ir ratios, as well as subchondritic Os/Ir ratios (Morgan et al., 1972, 1974; Korotev, 1994; James, 2002; Norman et al., 2002; Puchtel et al., 2008; Fischer-Gödde and Becker, 2012; Sharp et al., 2014). The non-chondritic HSE ratios have commonly been interpreted to reflect either the participation of impactors with bulk compositions outside of the range of presently sampled chondrites (Morgan et al., 1974; Norman et al., 2002; Puchtel et al., 2008; Sharp et al., 2014), or impactors with HSE that were variably fractionated as a result of metal–silicate or solid metal–liquid metal processing on their respective parent bodies (Goldstein et al., 1972; Morgan et al., 1972; Reed and Taylor, 1974; Korotev, 1994; James, 2002; Fischer-Gödde and Becker, 2012).

Numerous questions remain regarding the interpretation of HSE signatures in lunar impact melt rocks. How much did processes occurring within an evolving melt sheet modify the absolute and relative concentrations of HSE? For a given impact melt rock, what was the proportion of HSE derived from earlier impacts relative to the HSE added by the basin-forming event that purportedly created the melt rock? Related to this, can the HSE signatures of different generations of impactors be discriminated in a single rock? Where there are distinct HSE signatures present in different impact melt rocks from a given site, do the differences reflect chemical heterogeneities present in a single, basin-forming impactor, or are they the result of multiple smaller, crater-forming events involving chemically diverse impactors (e.g., Korotev, 1994)? Finally, are there unifying characteristics in the HSE signatures of different impact melt rocks from different sites that may argue for the global mixing of impactors that can potentially account for most of the chemical variations observed? For example, Fischer-Gödde and Becker (2012) concluded that linear trends observed on plots of HSE ratios from different lunar sites are indicative of the global mixing of two major HSE-rich components, one that was much like carbonaceous chondrites, and the other a metal component that formed as part of a crystallizing planetesimal core.

Here we report HSE concentration and Os isotopic data for eleven lunar impact-related melt rocks; two from the Apollo 15 site (melt rocks 15445 and 15455), and nine from the Apollo 16 site (two lithic clasts extracted from regolith breccia 60016, one lithic clast extracted from regolith breccia 65095, and six bulk impact melt rocks 60235, 60635, 62295, 63549, 67095 and 68416). The main objective of this work is to investigate the chemical nature of impactors contributing HSE to the Apollo 15 and 16 impact melt rocks. The data are combined with age data reported for the same rocks, and compared with HSE and age data for lunar impact rocks from other sampling sites (Norman et al., 2002; Puchtel et al., 2008; Fischer-Gödde and Becker, 2012; Sharp et al., 2014), allowing re-assessment of the extent of chemical homogeneity/heterogeneity among impactors involved in different basin-forming events, and placing constraints on the source of the impactors.

2. SAMPLES

Brief petrographic descriptions and a review of existing age data for Apollo 15 and 16 impact melt rocks are summarized in Table 1. Also included are age data for other lunar impact melt rocks for which complementary HSE concentrations and Os isotopic compositions exist.