IMPACTOR POPULATIONS AND LUNAR CRUSTAL COMPOSITIONS INFERRED FROM HIGHLY SIDEROPHILE ELEMENT COMPOSITIONS OF APOLLO 16 AND 17 MELT BRECCIAS.

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Introduction: Siderophile element compositions of lunar impact breccias provide a unique record of planetesimals traversing the inner Solar System. In order to provide better information about impactor populations responsible for the late heavy bombardment of the Moon, we measured the concentrations of highly siderophile elements in Apollo 16 and 17 melt breccias. Two samples of feldspathic granulitic breccias and an igneous norite clast were also analyzed to provide additional information about siderophile element compositions of pre-impact lithologies in the lunar crust.

Methods: 3g rock chips were powdered by hand in an agate mortar and pestle. ~250mg aliquots were dissolved and equilibrated with a mixed PGE+Re spike in 9ml carius tubes using reverse aqua regia heated to 260 C for 48 hours. PGE and Re were isolated from the rock matrix using anion exchange chemistry, and determined by isotope dilution using a quadrupole ICPMS. Total procedural blanks averaged ≤1pg for Ru and Ir, ≤2pg for Re, ≤7pg for Pt, and either 22pg or 74pg for Pd depending on carius tube glass stock. Splits of the carbonaceous chondrites Orgueil and Allende were analyzed to provide direct comparisons with data from other labs.

Samples: The suite of samples analyzed for this study includes: 10 impact melt breccias from the Apollo 16 site (60335, 60315, 62235, 63355, 65015, 65055, 66095, 67235, 68415, 68416); four samples of Apollo 17 aphanite (72215, 72235, 72255, 73235) and a related fragmental breccia (72275); two Apollo 17 feldspathic granulitic breccias (76235, 78155), and an igneous norite clast from 77035 previously classified as 'pristine' [1]. We also analyzed two metal beads from 60335 that resisted crushing during sample preparation.

Results: The *Apollo 16* breccias represent chemical groups defined by Korotev [2] on the basis of lithophile element compositions. The siderophile element compositions of these breccias reveal at least two fundamentally different patterns. Breccias classified as Group 1 (KREEP-rich, poikilitic textures) and Group 2 (lower incompatible elements, subophitic textures) have high concentrations of siderophile elements and patterns that are fractionated compared to CI-chondrites, with depletions of Ir and Pt relative to Re, Ru, and Pd (W-shaped patterns). Siderophile element ratios such as Re/Ir, Ru/Ir, and Pd/Pt correlate with absolute abundances, becoming more fractionated relative to CI at lower concentrations. In contrast, Group 3 breccias tend to have lower siderophile element abundances, and relatively flat CI-normalized patterns. The two metal beads from 60335 are highly enriched in PGE+Re (e.g., 1.3-1.6 ppm Ir, 3.7-4.2 ppm Pt), but they are somewhat heterogeneous in some ratios (e.g. Pd/Pt = 0.87-1.17).

The *Apollo 17 aphanites* have siderophile element compositions similar to the Apollo 17 poikilitic melt breccias [3], but in detail there are subtle differences. For example, on average the aphanites have lower PGE+Re concentrations, a more restricted range of compositions, and lower Pd/Pt and Ru/Ir ratios compared to the poikilitic breccias.

The two *feldspathic granulitic breccias* have high PGE+Re concentrations (6.6-20.2 ppb Ir, 0.5-1.8 ppb Re, 7.4-25.4 ppb Ru, 10.3-34.6 ppb Pt, 3.3-20.7 ppb Pd). Their CI-normalized patterns are relatively flat, with Re/Ir, Ru/Ir, and Pd/Pt ratios lower than those of the Apollo 17 poikilitic and aphanitic breccias. The *norite* clast has extremely low and barely detectable concentrations of PGE+Re, (Re 0.005 ppb, Ru 0.006 ppb, Pt 0.052 ppb, Pd 0.22 ppb).

Discussion: Highly siderophile element compositions of lunar impact melt breccias and associated lithologies inform us about:

* The number of different impact events represented in the Apollo collection.

* The provenance of planetesimals populating the inner Solar System four billion years ago.

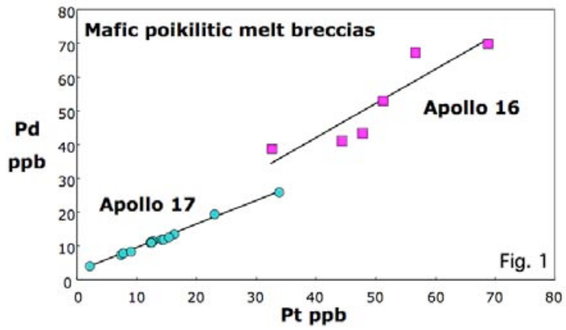
* Behavior of highly siderophile elements during emplacement of lunar melt breccia deposits.

* The siderophile element composition of the lunar crust.

How Many Impacts? The PGE+Re systematics of Apollo 16 breccias indicate at least two different types of impactors, and therefore at least two different impact events. This is consistent with recent 39Ar-40Ar dating of Apollo 16 melt breccias, which indicates subtle differences in age among petrographically and chemically defined groups [4].

Poikilitic melt breccias are sometimes thought to represent basin ejecta due to their mafic, KREEP-rich compositions. The Apollo 17 poikilitic breccias are probably impact melt from Serenitatis, although Haskin et al. [5] proposed that all of the mafic poikilitic breccias in the Apollo collection represent Imbrium ejecta. Compared to the Apollo 17 poikilitic breccias, the Apollo 16 mafic poikilitic (Group 1) melt rocks have higher siderophile element abundances, and they fall along a distinct trend to higher Pd/Pt ratios (Fig. 1). This suggests that the Apollo 16 and 17 KREEP-rich mafic melt breccias formed in different events, a conclusion consistent with the subtle difference in the age of these breccias: 3865 $\pm$ 10 Ma for Apollo 16 Group 1 vs. 3893 $\pm$ 9 Ma for the Apollo 17 poikilitic breccias [4,6]

We conclude that the siderophile element data are consistent with the hypothesis that the Apollo impact melt breccias formed in multiple impact events that occurred within a relatively narrow interval of time (100-200 million years).



Impactor Identification: Many of the melt breccias from both Apollo 16 and 17 sites have siderophile element patterns that are fractionated relative to CI-chondrites. The origin of this signature is enigmatic as most of the compositions seem to fall outside of the known range of chondritic groups. An enstatite chondrite impactor was inferred for the Apollo 17 poikilitic breccias based on their Ir-Ge-Au and PGE+Re compositions [3,7]. If the W-shaped patterns found in the Apollo 16 breccias are also the signature of enstatite chondrite impactors, then large planetesimals of enstatite chondrite bulk composition were common in the inner Solar System about 4 billion years ago.

The flat siderophile element patterns that distinguish the Apollo 16 Group 3 breccias require a different type of projectile. The Re/Ir and Pd/Pt ratios of these breccias are consistent with an ordinary chondrite impactor.

The provenance of enstatite and ordinary chondrites is thought to be predominantly in the inner Solar System. A source for the impactors in the asteroid belt is consistent with the size distribution of lunar craters [8]. Although the siderophile element compositions of comets are unknown, a reasonable assumption is that they resemble carbonaceous chondrites. The lack of carbonaceous chondrites signatures in lunar melt breccias argues against comets as a major source of impacting planetesimals during the late heavy bombardment of the Moon.

Siderophile element fractionation: Apollo 17 poikilitic breccias and Apollo 16 Group 1 and 2 breccias show well-defined trends to higher Re/Ir, Ru/Ir, and Pd/Pt with decreasing concentrations. Possible mechanisms to explain this fractionation include mixing of older crust into the melt breccias, and mobility of siderophile element-bearing phases such as fluids, metals, or sulfides. Large, euhedral sulfide crystals along vuggy zones that we interpret as vapor-outflow channels have been observed in some of these breccias (Fig. 2), raising the possibility that fluid transport may have fractionated the PGE. The heterogeneous siderophile element compositions of metal beads extracted from 60335 also suggests that variable incorporation of metal and/or associated sulfide during emplacement or sampling of these breccias may have contributed to the range of compositions observed in these breccias.

Much of the spread in siderophile element ratios in these breccias can be reduced by subtraction of a hypothetical component inferred from the intercept values calculated from linear arrays (e.g., Ir vs. Re). This suggests that mixing with a component of relatively constant composition is responsible for at least some of the observed variation in siderophile element ratios. However, residual variations in Re/Ir and Pd/Pt remain even after subtraction of such a hypothetical component, pointing toward more complex processes affecting siderophile element compositions in lunar melt breccias.

Fig. 2
Euhedral sulfide in 77035. Grain is ~0.5 mm wide.

References: [1] Warren and Wasson 1979 PLPSC 10, 583-610. [2] Korotev 1994 GCA 58, 3931-3969. [3] Norman, Bennett, & Ryder 2002 EPSL 202, 217-228. [4] Norman, Duncan, & Huard 2006 GCA submitted. [5] Haskin, Korotev, Rockow, & Jolliff 1998 MAPS 33, 959-975. [6] Dalrymple & Ryder 1996 JGR 101, 26069-26084, 10.1029/96JE02806. [7] Kring & Cohen 2002 JGR 107, 10.1029, 2001JE001529. [8] Strom, Malhotra, Ito, Yoshida, & Kring 2005 Science 309, 1847-1850.