PROVENANCE OF IMPACT MELT AND GRANULITE CLASTS IN LUNAR METEORITE PCA 02007.

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Introduction: Hypervelocity impacts shape the surfaces of terrestrial planets and asteroids. The rocks produced by impacts record information about the collisional history of their parent Solar System bodies. We investigated lunar meteorite Pecora Escarpment (PCA) 02007, a feldspathic regolith breccia [1-3], to better understand the impact history of the Moon. We performed petrographic and geochemical analyses of PCA 02007's impact melt and granulite clasts—fragments of rock produced by impacts—to find compositional clues to the lunar provenance of the clasts.

Samples and Methods: A doubly polished ~100 µm thick section of PCA 02007,37 was prepared. Clast components were characterized with a petrographic microscope and a JEOL-5910LV scanning electron microscope. Clast chemistry was determined with a Cameca SX100 electron microprobe using a 15 kV, 15 nA beam (for silicates) or a 20 nA beam (for metals) with a 1 µm (for minerals) or 20 µm (for bulk clast averages) beam diameter. Trace element concentrations of selected clasts were measured with laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS) on a Varian ICP-MS. Circular spots 50 µm in diameter were ablated from clasts for ICP-MS analysis; for larger clasts, analyses from several areas were averaged to determine the bulk trace element composition by a method similar to [3]. ICP-MS data were reduced with Glitter software using Ca as the external standard.

Results: *Petrography*. PCA 02007 is composed of mineral, glass, impact melt, and granulite clasts set in a very fine-grained clastic matrix [1-3]. Figure 1a shows a representative area of the sample; note the agglutinate (A) and the impact-derived glass bead (B), which represent regolith components. The clast population is dominated by impact melts and shocked ferroan anorthosite fragments. Our study focuses on impact melt-derived clasts and granulite clasts 100-500 µm in diameter. These clasts are subdivided into four textural categories: granoblastic granulites, e.g., Fig. 1b; clast-rich impact melts, (>25 % clasts), e.g., Fig. 1c; clast-bearing impact melts (10-25 % vol. clasts); and clast-free impact melts (<10 % vol. clasts), e.g., Fig. 1d, following the criteria of [4].

Granulite clasts (Fig. 1b) are composed of equidimensional plagioclase crystals enclosing rounded olivine and pyroxene crystals; they may also contain accessory iron-nickel metal, troilite, or ilmenite.

Impact melt clasts (e.g., Fig. 1c-d) have a wide range of textures. They are typically composed of euhedral plagioclase crystal laths and glassy interstitial melt occasionally containing small olivine crystals and immiscible iron-nickel metal and troilite. Angular olivine, pyroxene, plagioclase, and chromite clasts in clast-bearing and clast-rich impact melt clasts are relict target rock material that was entrained in melt. In general, clast-bearing and clast-rich impact melts have smaller plagioclase crystals than clast-free melts.

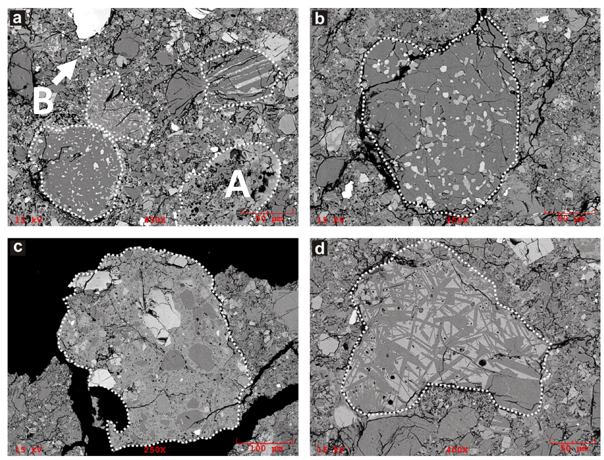

Figure 1. Back-scattered electron (BSE) images of selected clasts from PCA 02007. (a) Overview of matrix showing agglutinate A at lower right, glass bead B at upper left, granoblastic granulite at lower left, and two clast-bearing impact melts. (b) Granoblastic granulite. (c) Clast-rich impact melt. (d) Clast-free impact melt. In all images, plagioclase is dark gray; mafic phases are light gray; and oxides, sulfides and metals are bright white. The glass slide and fractures appear black. Clasts are outlined by a dotted white line.

Mineral chemistry. We analyzed the mineral chemistry of phases in 15 impact melt and 4 granulite clasts. All plagioclase is highly calcic (An_{92} to An_{98}, with $Or_{<0.4}$ and generally $Or_{<0.1}$). Plagioclase crystals that grew from impact melt cluster between An_{95} and An_{97}, whereas plagioclase clasts entrained in melt are more variable, ranging from An_{92} to An_{98}. Pyroxene compositions are particularly diverse ($En_{39\text{-}76}Wo_{1\text{-}37}Fs_{16\text{-}48}$). Thermometric modeling of a two-pyroxene pair in a granulite clast using QUILF software [5] yields a best fit for 1060 °C (1 bar) / 1057 °C (1 kbar) / 1046 °C (5 kbar). Olivine compositions range from Fo_{52} to Fo_{81}. Most olivine contains about 0.3 wt% CaO, similar to the range of CaO in ferroan anorthosite and mare basalt olivine [6]. Metal grains range from 0.13 to 1.09 wt. % Co and 1.7 to 16.6 wt. % Ni. The Co/Ni ratios of these metal grains are similar to Co/Ni ratios of meteoritic metal, not metal endogenous to lunar basalts [7].

Bulk clast chemistry: major and trace elements. Figure 2 shows that 15 out of 19 clasts have affinities to ferroan anorthosites. Two clasts have compositions similar to Mg-suite rocks.

Seven of the ten clasts analyzed for trace elements show positive Eu anomalies (chondrite-normalized Eu/[(Sm+Gd)/2] ranging from 1.4 to 5.8), again consistent with a derivation from feldspathic target rocks [8]. However, these feldspathic clasts have higher Sc contents (Fig. 3) than Apollo 16 Group 4 feldspathic impact melts, within the range of bulk composition of feldspathic lunar meteorites and feldspathic impact melt clasts in these meteorites [3].

One impact melt clast shows a negative Eu anomaly (0.85), suggesting that it was derived from mare basalt target rock [8]. This clast and another impact melt clast share Sc abundances (~50 ppm Sc) similar to very low titanium (VLT) mare basalts (Fig. 3).

Finally, all PCA 02007 impact melt and granulite clasts analyzed for trace elements are KREEP-poor (containing only 0.1 to 1 ppm Th) compared with Apollo mafic impact melts. Samarium concentrations (Fig. 3) indicate the clasts are most similar to the Group 3 and 4 Apollo feldspathic impact melts [9].

Summary: We suggest that the impact melt and granulite clasts of PCA 02007 were derived from melting of feldspathic highlands rocks with exotic components from Mg-suite (see Fig. 2) and mare basalt (see Fig. 3) lithologies. Since PCA impact melt and granulite clasts are KREEP-poor compared to most Apollo impact melt groups (Fig. 3), it is likely that the impacts that contributed material to PCA took place in KREEP-poor regions of the Moon with mainly feldspathic lithologies (the Feldspathic Highlands Terrane [10]), not KREEP-rich regions dominated by mare basalt lithologies (the Procellarum KREEP Terrane [10]).

The formational context of the impact melt and granulite clasts in PCA 02007 will be further constrained by Ar-Ar dating (in progress), which may also provide information about the impact flux in regions of the Moon unsampled by the Apollo and Luna missions.

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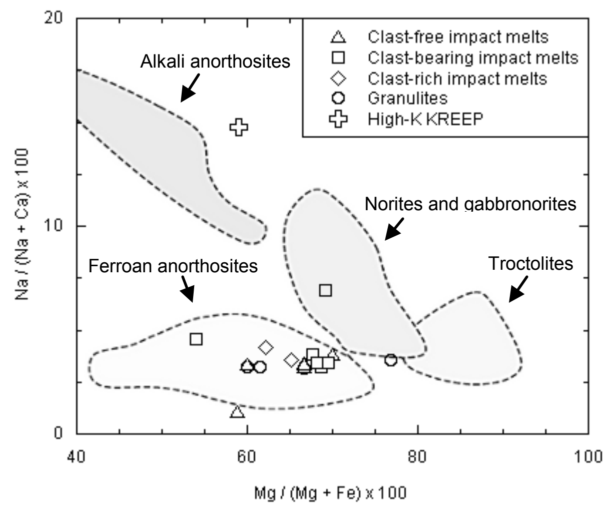

Figure 2. Bulk PCA clast molar Na / (Na + Ca) x 100 vs. molar Mg / (Mg + Fe) x 100 compared with high-K KREEP [11] and highland rock suite (ferroan anorthosite, Mg-suite, and high-alkali-suite) compositions from Apollo samples listed in [12].

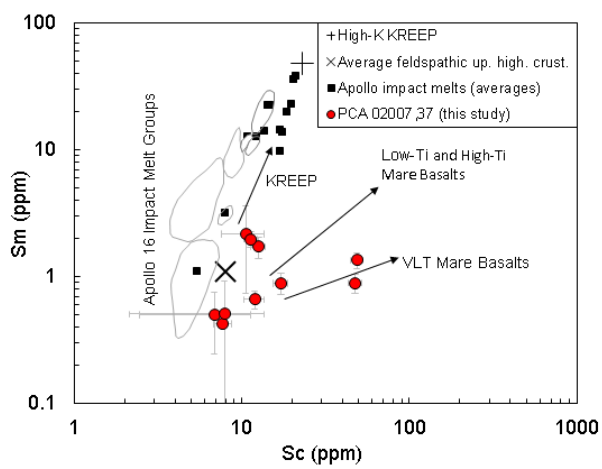

Figure 3. Bulk PCA clast Sm (ppm) vs. Sc (ppm) compared with Apollo 16 impact melt groups [9, 13], high-K KREEP [11], averages of Apollo impact melt groups [13], and the average composition of the upper crust of the lunar highlands [14]. Error bars represent one standard deviation of the range of values measured in that clast (i.e., they reflect clast heterogeneity, not measurement precision).

References: [1] Korotev R. L. et al. (2006) *GCA* 70, 5935–5956. [2] Day J. M. D. et al. (2006) *GCA* 70, 5957–5989 [3] Joy K. H. et al. (2010) *MAPS* 45, 917–946. [4] Stőffler et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 51-70. [5] Andersen et al. (1993) *Comp. &. Geosci.* 19,:1333-1350. [6] Steele et al. (1975) *Proc. Lunar Sci. Conf. 6th*, 451-467. [7] Papike J. J. et al. (1991) *Lunar Sourcebook*, 121-181. [8] Vaniman et al. (1991) *Lunar Sourcebook,* 5-26. [9] Korotev R. L.(1994) *GCA 58,* 3921-3969. [10] Jolliff et al. (2000) *JGR* 105, 4197-4216. [11] Warren (1999) *LPI Tech. Rept.* 89-03, 149-153. [12] Taylor G. J. et al. (1991) *Lunar Sourcebook*, 183-284. [13] Jolliff B.L. (1998) *Int. Geo. Rev. 40,* 916-935. [14] Korotev R.L. et al. (2003) *GCA* 67, 4895-4923.