IMPACT MELTS AND GRANULITES IN THE LUNAR METEORITE PCA 02007. William M. Vaughan[1], Axel Wittmann[2, 3], Katherine H. Joy[2, 3], and David A. Kring[2, 3]. [1]Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Ave., Chicago, IL 60637, USA, wvaughan@uchicago.edu, [2]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, USA. [3]NASA Lunar Science Institute, Wittmann@lpi.usra.edu; Joy@lpi.usra.edu; Kring@lpi.usra.edu

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 the lunar meteorite Pecora Escarpment (PCA) 02007, a feldspathic regolith breccia [1-5], 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 determine their lunar provenance and reconstruct their formational setting.

Samples and Methods: Three doubly polished sections (one ~100 µm thick, two 30 µm thin) of PCA 02007,37 were prepared. Clast components were characterized with a petrographic microscope and a JEOL scanning electron microscope. A Cameca SX100 electron microprobe was used to determine the mineral chemistry and bulk composition of impact melt clasts, granulite clasts, and metal particles from the thick section. Silicates were analyzed with a 15 kV, 15 nA beam of 1 µm diameter. Bulk clast compositions were derived using the same analytical setup with a defocused 20 µm diameter beam. An estimate of the bulk composition of the thick section was made from an average of 29 defocused beam analyses of the matrix and is presented in Table 1. Metals were analyzed with a 15 kV, 20 nA beam of 1 µm diameter. The NIH software ImageJ [6] was used to measure the percent area of mineral phases from back-scattered electron images to determine mineral modes.

Results: *Petrography*. PCA 02007 is a feldspathic regolith breccia composed of mineral, glass, impact melt, and granulite clasts set in a very fine-grained clastic matrix [1]. 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, although several fragments of ferroan anorthosite and low-Ti basalt occur. Our study focuses on 15 impact-melt clasts and 4 granulite clasts from 100 to 500 µm in diameter. These clasts are subdivided into four textural categories: granoblastic granulites, clast-free impact melts, clast-bearing impact melts, and clast-rich impact melts, following the criteria of [7].

Figure 1b shows a typical granoblastic granulite. Granulite clasts are composed of equidimensional plagioclase crystals enclosing rounded-to-sub-rounded oli-vine and pyroxene crystals; they may also contain iron-nickel metal, troilite, or ilmenite as accessory phases.

Impact melt clasts are composed of euhedral plagioclase crystal laths; glassy interstitial melt, occasionally containing small olivine crystals and immiscible iron-nickel metal and troilite; and olivine, pyroxene, plagioclase, and chromite clasts. The relative proportions of crystals, clasts, and melt vary between different categories of impact melts: clast-free impact melts contain less than 10 vol. % clasts, clast-bearing impact melts contain between 10 and 25 vol. % clasts, and clast-rich impact melts contain more than 25 vol. % clasts [7]. Figure 1c shows a clast-rich impact melt with a wide range of clast sizes but uniformly very fine-grained (<30 µm), almost cryptocrystalline, plagioclase crystals. Figure 1d shows a clast-free impact melt with fine-grained (30-300 µm), euhedral plagioclase crystal laths. In general, clast-rich impact melts have smaller plagioclase crystals.

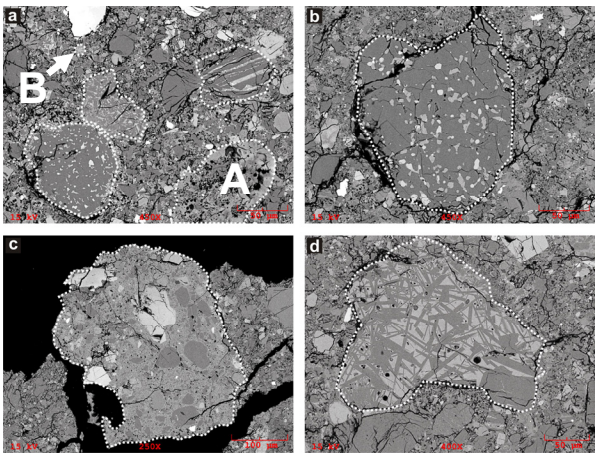

Figure 1. Back-scattered electron images of selected clasts from PCA 02007. (a) Overview of matrix showing agglutinate A at lower right, glass bead B at upper left, granoblastic granulite at lower left, and two clast-bearing impact melts. (b) Granoblastic granulite. (c) Clast-rich impact melt. (d) Clast-free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

Mineral chemistry. We analyzed the mineral chemistry of 19 impact melt and granulite clasts in PCA 02007. All analyzed plagioclase is highly calcic (An_{92} to An_{98}, Fig. 2) with $Or_{<0.4}$ and generally $Or_{<0.1}$. Plagioclase crystals that grew in impact melts cluster between An_{95} and An_{97}, whereas plagioclase clasts and plagioclase granoblasts are more variable—for example, they occupy the An_{92} and An_{98} extremes. Pyroxene and olivine clasts show more diversity in composition (Fig. 3). Pyroxene clast compositions are particularly diverse ($En_{39-76}Wo_{1-37}Fs_{16-48}$). Olivine clast compositions are generally magnesian and range from Fo_{52} to Fo_{81}. Most olivine contains about 0.3 wt% CaO. Co/Ni ratios of the metal grains in PCA 02007 are similar to Co/Ni ratios of meteoritic metal [8], not ratios of metal found in Apollo rocks and soils (Fig. 4).

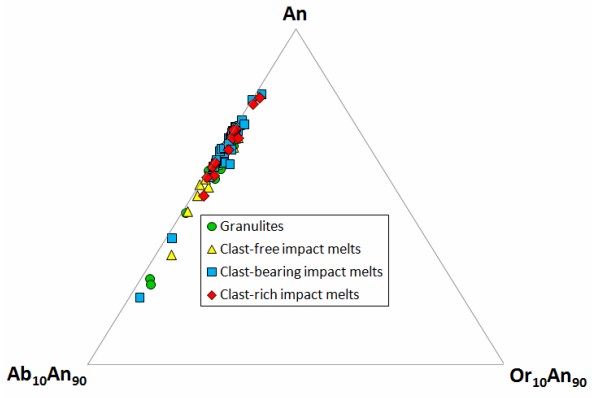

Figure 2. Composition of plagioclase in impact melt and granulite clasts from PCA 02007.

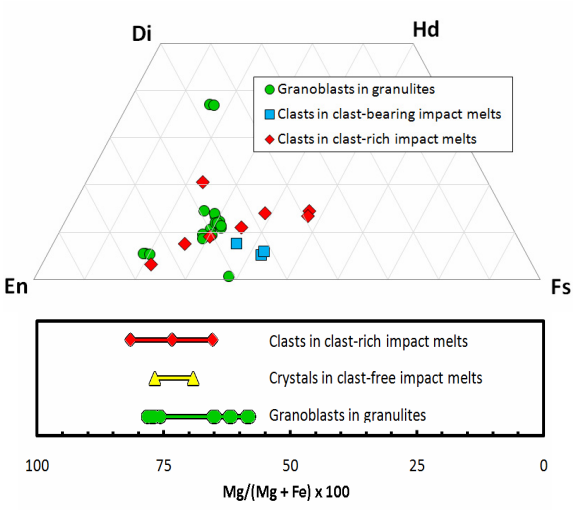

Figure 3. Composition of pyroxene (top) and olivine (bottom) in impact melt and granulite clasts from PCA 02007.

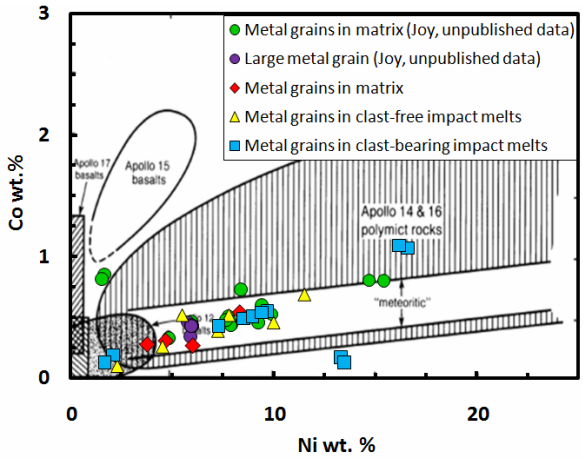

Figure 4. Composition of metal grains in PCA 02007 compared with compositions of metal grains from Apollo samples and meteoritic metal [8].

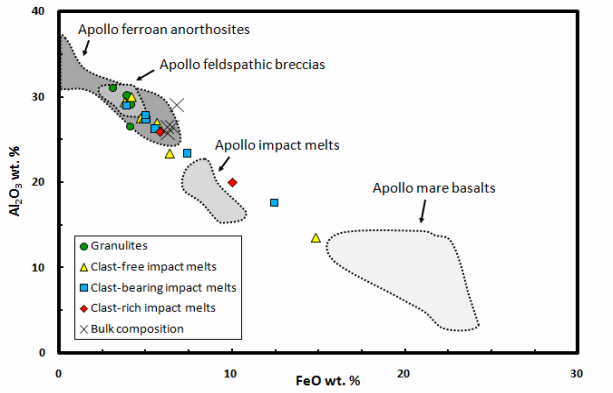

Figure 5. Bulk clast wt. % Al_2O_3 vs. wt. % FeO compared with rock compositions from Apollo samples [9-11].

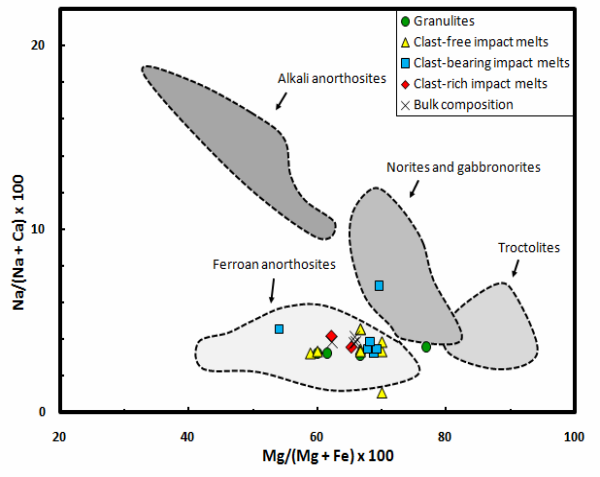

Figure 6. Bulk clast Na # vs. Mg # compared with highland rock suite (ferroan anorthosite, Mg-suite, and high-alkali-suite) compositions from Apollo samples [12].

Discussion: *Impact setting of impact melts and granulites.* Impactites sampled in PCA 02007 are products of several impact cratering processes: granulites are probably impact melts that have been buried and thermally metamorphosed by subsequently deposited ejecta blankets; they were therefore likely formed after energetic impact events that produced craters >30 km in diameter [13]. Impact melt-bearing fallback lithologies (clast-poor, clast-bearing, and clast-rich impact melts) likely come from proximal, near-surface ejecta deposits of impact craters [14]; glass beads could record contributions from more distal impact cratering events; and agglutinates record very small, local impact cratering events.

Parent rocks of impact melts and granulites. The bulk compositions of impact melt and granulite clasts record information about their parent target rocks. Figure 5 shows that the majority of impactite clasts in PCA 02007 are similar in composition to Apollo 16 feldspathic breccias, feldspathic melt breccias, and pristine ferroan anorthosites, indicating that their parent rocks were highly feldspathic. The bulk composition of PCA 02007 (Table 1, Fig. 5) is located at the Fe-rich end of the feldspathic lithology region, suggesting that PCA 02007 is a mix of highly feldspathic lithologies and more mafic material: see also [1] and [15]. PCA 02007 contains no significant KREEP component (no high-Na # rock types, Fig. 6: see also [1-5, 15]) so it may have been consolidated in a region of the moon unsampled by the Apollo and Luna missions.

Three impactite clasts are more mafic than feldspathic (Figs. 5 and 6). A Fe-rich (bulk 15 wt. % FeO) clast-free impact melt with a low Na concentration (0.06 wt. % Na_2O) has high Ti (>0.5 wt. % TiO_2), suggesting it was derived from mixing feldspathic and mare basalt lithologies. Two clasts have a Mg-suite affinity: a clast-bearing impact melt with a composition similar to Apollo norite/gabbronorite (Fig. 6) and a magnesian granulite (Fig. 6). Trace element studies will constrain the provenance of this mafic material. These studies may also reveal whether there are any unusual feldspathic KREEP-rich impact melt clasts in PCA 02007, like those reported in other lunar meteorites [15].

Conclusions and Outlook: PCA 02007 is a feldspathic regolith breccia with numerous impact melt and granulite clasts. These clasts are derived mainly from feldspathic highlands rocks, with exotic components from mare basalt and Mg-suite lithologies.

More than one impact event contributed to the formation of this rock, because its components were formed in different impact settings and were derived from at least three different types of parent rock. However, the number of impact events recorded in PCA 02007 is not possible to determine from available data. This number may be constrained by future Ar-Ar dating of the impact melt rock clasts, which will also provide information about the impact flux in regions of the Moon not sampled by the Apollo and Luna missions.

References: [1] Korotev R. L. et al. (2006) *Geochim. Cosmochim. Acta* 70, 5935–5956. [2] Zeigler R. A. et al. (2004) *LPS* XXXV, Abstract #1978. [3] Day J. M. D. et al. (2006) *Geochim. Cosmochim. Acta* 70, 5957–5989. [4] Joy K. H. et al. (2006) *LPS XXXVII*, Abstract #1274. [5] Taylor L. A. et al. (2004) *LPS XXXV*, Abstract # 1755. [6] Rasband W. S. ImageJ, National Institutes of Health, http://rsb.info.nih.gov/ij/. [7] Stőffler et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 51-70. [8] Papike J. J. et al. (1991) *Lunar Sourcebook*, 121-181. [9] Jolliff B. L. et al. (1998) *Int. Geo. Rev.* 40, 916-935. [10] Korotev R. L et al. (1994). *Geochim. Cosmochim. Acta* 58, 3931-3969. [11] Wieczorek M. A. et al. (2006) *Rev. Min. Geochem.* 60, 221-364. [12] Taylor G. J. et al. (1991) *Lunar Sourcebook*, 183-284. [13] Treiman A.H. et al. (2010) *Met. Planet. Sci*. 45, 163-180. [14] Stőffler D. et al. (2006) *Rev. Min. Geochem.* 60, 519-596. [15] Joy K. H. et al. (2010). *Met. Planet. Sci.* (In press).

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Table 1. Bulk composition (wt. % oxides) of PCA 02007. Totals for this study normalized to 100 wt. %.

	SiO_2	Al_2O_3	TiO_2	Cr_2O_3	FeO	MnO	MgO	CaO	NiO	Na_2O	P_2O_5	K_2O	Total
This study	44.14	26.46	0.31	0.13	6.57	0.06	6.08	15.74	0.10	0.35	0.03	0.04	100
St. dev.	*1.07*	*3.80*	*0.17*	*0.17*	*2.98*	*0.07*	*2.61*	*1.94*	*0.05*	*0.12*	*0.04*	*0.04*	
Joy et al. [4, 15]	43.41	25.71	0.28	0.171	6.3	0.09	6.8	15.19	0.05	0.36	0.03	0.03	98.42
Day et al. [3]	38.6	29.06	0.28	0.17	6.8	0.09	7.4	17.26	0.04	0.38	0.08	0.05	100.21
Korotev et al. [1]	44.80	26.50	0.29	0.16	6.26	0.09	6.70	15.40	0.05	0.33	0.03	0.02	100.60