PETROGRAPHY AND PROVENANCE OF IMPACT MELT AND GRANULITE PARTICLES FROM THE ANCIENT REGOLITH BRECCIAS 60016, 61135, AND 66035. A. Wittmann[1,2], Thomas Lapen[2,3], Timothy D. Swindle[2,4], and David A. Kring[1,2]. [1]Lunar & Planetary Institute, Houston, TX. 77058, wittmann@lpi.usra.edu; [2]NASA Lunar Science Institute; [3]Department of Earth & Atmospheric Sciences, University of Houston, Houston, TX 77204; [4]Lunar & Planetary Laboratory, University of Arizona, Tucson AZ 85721.

Introduction: The Apollo 16 landing site is characterized by a landscape that was interpreted as ejecta from the Imbrium impact, the Cayley Plains, that blanket the Descartes Mountains, more proximal ejecta from the Nectaris impact basin [1], or a different ejecta facies from the Imbrium impact basin [2]. A suite of regolith breccias that was returned by Apollo 16 has been identified as fossil regolith that formed ~4 Ga ago [3]. We study impact melt and granulite particles in three of these regolith breccias in order to identify precursor rocks, meteoritic contamination, and relative magnitudes of impact events responsible for their formation during the basin forming epoch of the Moon.

Samples & Methods: The 3 1”-diameter thick sections 60016,278, 61135,68, and 66035,49 were studied by optical microscopy and scanning electron microscopy. We found 39 impact melt particles and 8 granulite particles larger than ~150 µm in size. Geochemical analyses were performed on constituent melt phases, including their crystallization products, and entrained target clasts. Bulk major element concentrations derived from the average of several 20 µm-diameter defocused beam analyses (DBA) on representative areas were determined by electron probe microanalysis. Trace element concentrations of 5 melt and 5 granulite particles were determined from the the average of several 50 µm in diameter spots measured by laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS).

Results: *Petrography:* The 39 melt particles studied range in size between 2.44 and 0.16 mm across their widest section. The 12 melt particles in thick section 66035,49 are on average more strongly fractured than the 12 in thick section 60016,278 and the 15 in 61135,68. Particle shapes range from angular to subrounded and spherical, and some that are ameboid. Most particles are angular with sharp contacts, but 2 are spherules: 1 in 66035,498 is a vitrophyre, and 1 in 60016,27 is crystallized. One vitrophyre in 60016,278 displays a quench zone around its margin, and another one in 66035,49 has a possible accretionary rim of fine dust surrounding a micro-vesicular quench zone.

Glass-rich vitrophyres: One particle in 61135,68 is a homogeneous, brown, vesicular glass. Five particles retain larger areas of glass but crystallized variable phenocrysts and are associated with Fe-Ni metal blebs and troilite. Two of these glassy particles, 1 in 60016,278 and 1 in 66035,49, retain >50 vol% glass and crystallized Mg-rich olivine (Fo_{96-97} and $_{87-89}$). Another one in 66035,49 is composed of glass and cryptocrystalline feldspar. The 2 particles in 61135,68 that retain <50 vol% feldspathic glass mostly devitrified to plagioclase and mafic mesostasis, are vesicular, and contain lithic clasts.

Glass-poor vitrophyres: Nineteen melt particles (6 in 60016,278, 8 in 66035,49, and 5 in 61135,68) are vitrophyres with hyalophitic to intersertal textures composed of fine (30-300µm)- to very fine (<30µm)-acicular plagioclase ($Ab_{2-11}An_{98-89}Or_{0-0.9}$, n=25) in a mafic mesostasis. One of these clasts is clast-poor (<10 vol.% clasts), all others contain >10 vol.% lithic clasts, mostly fragments of plagioclase ($Ab_{0-24}An_{100-74}Or_{0-2.9}$, n=101), olivine ($Fo_{55-84}$, n=48) and pyroxene ($En_{37-78}Fs_{9-42}Wo_{2-45}$, n=28). Rare inclusions of ZrO_2, orthoclase, whitlockite, and apatite clasts were found as well. These particles frequently contain clasts of impact melts as inclusions, and one particle in 61135,68 is a composite of an intergranular, crystallized melt particle that is fused to a hyalophitic vitrophyre.

Crystallized melt particles: Fifteen melt particles (5 in 60016,278, 2 in 66035,49, and 9 in 61135,68) are crystallized with fine- to very fine-grained plagioclase ($Ab_{3-22}An_{97-77}Or_{0-2.3}$, n=75) that is intergrown with zoned pyroxene ($En_{46-82}Fs_{11-30}Wo_{3-40}$, n=56) ± olivine ($Fo_{60-85}$, n=77), ilmenite, troilite, and Fe-Ni-metal; rare SiO_2, ZrO_2, and whitlockite were found as well. Their textures range from sub-ophitic to intergranular and poikilitic. This melt particle type is usually angular and contains very variable amounts of partly digested lithic clasts, which are sometimes hard to recognize. Only 1 particle in 66035,49 and 4 in 61135,68 appear clast-free.

Granulite particles: All 8 granulites are subangular to angular in shape. Three in 60016,278, 1 in 66035,49 and 3 in 61135,68 are granoblastic with minor, fine-grained, euhedral pyroxene ($En_{44-77}Fs_{9-35}Wo_{2-44}$, n=53, 6 clasts) and/or olivine (Fo_{66-76}, n=28, 5 clasts) that grew at grain-boundaries of >100 µm plagioclase ($Ab_{3-7}An_{97-93}Or_{0-0.4}$, n=55). One granulite in 60035,49 is poikiloblastic and crystallized low-Ca pyroxene ($En_{64-68}Fs_{28-31}Wo_{2-9}$, n=7), which encloses fine-grained, round plagioclase ($Ab_{5-6}An_{95-94}Or_{0-0.3}$, n=8). Accessory phases are rare chromite, ilmenite, and troilite. Only the most fine-grained granulite carries an identifiable lithic clast (in 60016,278).

Two-pyroxene thermometry: Thermochemical modeling using the QUILF-program [4] indicates augite – low-Ca pyroxene pairs in 2 crystallized melt particles (1 each in 60016,278 and 61135,68) equilibrated at 1040 to 1070 °C. Low-Ca pyroxene–augite pairs in 4 granoblastic granulites (3 in 60016,278 and 1 in 66035,49) likewise indicate equilibration between 870 and 1080 °C; and a pigeonite pair in the poikiloblastic granulite in 66035,49 suggests equilibration at 1030 to 1080 °C.

Metal compositions: Fe-Ni metal grains in 21 of the 39 impact melt particles (8 in 60016,278, 6 in 66035,49, 7 in 61135,68) have Co/Ni ratios that indicate a meteoritic origin [5].

Bulk Compositions: Preliminary DBA data: Most melt and granulite particles indicate affinities to alkali-gabbro norites and ferroan anorthosites (FAN) in the *Mg# vs Na/(Na+Ca)* and *Mg# vs* Al_2O_3 diagrams of [6]. One glass-rich vitrophyre in 60016,278 indicates exclusive derivation from a Mg-suite precursor. In the *MgO vs* Al_2O_3, and *FeO* diagrams of [7], all melt and granulite particles except the one with a strong affinity to troctolite / Mg-suite, indicate variable mixtures between FAN and norite or KREEP basalt. In the Al_2O_3 *vs MgO+FeO* diagrams of [7], most particles plot close to the field for Apollo regolith breccias, but 1 vitrophyre and 1 crystallized melt particle in 60016,278, 3 vitrophyres and the granoblastic granulite particle in 66035,49 and 1 crystallized melt particle in 61135,68 show a stronger affinity to Apollo KREEP-bearing impact melt rocks. Overall, crystallized melt particles tend to have higher concentrations of K_2O than vitrophyres and granulites, and thus suggest a larger KREEP component [7]. In the *5x(Fe-Ti) vs Al vs 25xTi* - diagram of [8] and [9], most particles plot close to the typical composition for Apollo 16 soils. Vitrophyre and granulite particles tend towards Al-rich compositions, while crystallized melt particles show a distinct HKFM or KREEP component; only the poikiloblastic granulite particle shows a distinct affinity towards mare.

LA-ICP-MS data: Two crystallized melt particles and 3 granulites from 60016,278, and 1 glass-rich vitrophyre, 1 glass-poor vitrophyre, and 1 crystallized melt particle in 60035,49 were analyzed by LA-ICP-MS. All granulites exhibit low concentrations of REE between ~0.1 and 20 x CI-chondrites and positive Eu-anomalies that is least distinct in the poikilitic granulite in 66035,49. The REE pattern in this particle is also the only one that exhibits a positive slope ($La/Lu_{(norm.)}$ =0.07), indicating lower relative enrichment in light-REE than heavy-REE. The 3 crystallized melt particles show negative Eu-anomalies and strong enrichment in REE relative to CI-chondrites. Their REE patterns are most similar to those [6] calculated for an evolved mafic-ferroan FAN-suite parent magma composition. In the *Th vs Sm/Eu (CI-normalized)* and *Sm vs Th* diagrams of [6], the crystallized melt particles plot in the area of KREEP-impact-melt breccias, while the vitrophyres and granulites plot in the non-mare field for anorthosites and feldspathic breccias.

Discussion: Based on textural similarities and the relative amounts of clasts that survive in impact melts of smaller craters, [10] concluded that impact melts in Apollo 16 breccias (specifically 66035) likely formed in cratering events equivalent in magnitude between the 28 km Mistastin and the 100 km Manicouagan impact structures on Earth. These craters formed melt-sheets with maximum thicknesses of ~80 to ~1400 m [11; 12] According to [10], subophitic-textured, crystallized melt particles devoid of lithic clasts may indicate formation in larger melt volumes, while vitrophyres and clast-bearing melt particles are more likely to be related to smaller melt volumes and possibly ejecta. Our compositional data suggests most vitrophyres, which do not allow constraints for the magnitude of the impact that formed them, were mainly produced from highlands crust.

Interestingly, most granulites seem to have non-mare, and non-KREEP precursors as well. This is in agreement with the scarcity of mare- and KREEP-basalt fragments in these ancient regolith breccias [3]. Consequently, the formation of the granulites in the Apollo 16 ancient regolith breccias appears to be related to impact heating, and thus, the presence of hot ejecta blankets or large amounts of impact melt. With our samples, this suggests the granulites formed during impact events that did not involve mare or KREEP components. Moreover, it is intriguing that the poikiloblastic, mafic granulite in 66035,49 may indicate formation from precursors dominated by a noritic component, e.g., from its Sc abundance [13]. This, in turn, could mean that it formed in a very large impact event unrelated to Imbrium that excavated and metamorphosed material from the lower lunar crust.

Acknowledgments: W. W. Satterwhite, A. H. Peslier, D. K. Ross, G. A. Robinson, R. Harrington, (NASA-JSC).

References: [1] Muehlberger et al. (1980), *Proc. Conf. Lunar Highlands Crust*, 1-50. [2] Hodges & Muehlberger (1981), *USGS Prof. Pap. 1048*, 215-230. [3] McKay et al. (1986), *JGR 91-B4*, D277-D303. [4] Andersen et al. (1993), *Comp. & Geosci. 19*, 1333-1350. [5] Ryder et al. (1980), *Proc. LPSC 11*, 471-479. [6] Taylor (2009), *Elements 5,* 17-22. [7] Korotev (2005), *Chemie der Erde 65*, 297-346. [8] Zellner et al. (2002), *JGR 107-E11*, 5102. [9] Spudis (2002) *LPS XXXIII*, abstract # 1104. [10] Grieve et al. (1974) *Proc.LPSC 5*, 261-273. [11] Grieve (1975) *GSA Bull. 86*, 1617-1629. [12] O'Donnell-Cooper & Spray (2010) *LPS XLI*, abstract # 1755. [13] Korotev (1994) *GCA 58*, 3931-3969.