EVIDENCE FOR MULTIPLE IMPACT EVENTS FROM CENTIMETER-SIZED IMPACT MELT CLASTS IN APOLLO 16 ANCIENT REGOLITH BRECCIAS: SUPPORT FOR LATE STAGE HEAVY BOMBARDMENT OF THE MOON. Takafumi Niihara[1,2], Sky P. Beard[2,3], Timothy D. Swindle[2,3], and David A. Kring[1,2], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute. 3600 Bay Area Boulevard, Houston, Texas 77058, USA. (E-mail: niihara@lpi.usra.edu). [2]NASA Lunar Science Institute. [3]Lunar and Planetary Laboratory, University of Arizona.

Introduction: Previous studies of lunar lithologies produced a series of impact reset ages that clustered around 4.0-3.8 Ga [e.g., 1,2] and were interpreted as evidence of a short and intense period of impact bombardment [3], ranging from 20 to 200 million years long [4]. Others have suggested, in contrast, that the Ar-Ar ages all represent various degrees of partial re-setting by the Imbrium or some other impact [5-7], or that many ages that represent older impacts were misinterpreted [8], and that the cluster of ages is misleading.

We have been probing that issue with a series of studies of Apollo 16 impact melts to determine if they were produced by a single event or multiple events. Norman and others [9] were the first to attempt this test with a suite of rock-scale impact melts [10] that have both a range of texture and a range of Ar-Ar ages. Among 25 samples, they found ages from 3.75 to 3.96 Ga and suggested those ages were produced by at least four different impact events. We have been pursuing a similar study with impact melt clasts in regolith breccias, beginning with breccias 60016 and 65095 [11,12]. Here we describe additional analyses of impact melt clasts from breccia 61135 and then compile our results for all Apollo 16 melt clasts.

Samples and Analytical Procedure: 61135 is an ancient regolith breccia from Apollo 16 station 1 that was lithified at 3.8 Ga [e.g., 13]. We were allocated thin-sections from two centimeter-sized clasts of impact melt: Clast 1 (,67) and Clast 2 (,66). Adjacent splits from the same clasts were also allocated for Ar-Ar chronological work that is underway. We conducted petrological analyses using optical microscopes at LPI and scanning electron microscopes (JEOL JSM-7600F and JSM-5910LV) and an electron probe micro analyzer (CAMECA SX-100) at NASA JSC.

Result: *Petrography and mineral compositions:* Clast 1 (,67) consists of three regions, referred to here as R1, R2 and R3, with indistinct boundaries. All regions contain tiny droplets of Fe-Ni metal-troilite-schreibersite mixture (<60 μm size). Fe-Ni metal has a meteoritic composition (Ni=3.0-3.7 wt.% and Co=0.3-0.4 wt.%). R1 consists of relict plagioclase ($An_{97.0-94.6}Ab_{5.1-3.0}Or_{0.3-0}$) with Na-rich overgrowth ($An_{93.2}Ab_{6.4}Or_{0.5}$) and pyroxene ($En_{70}Wo_{12}$; Mg#=79-80) in an aphanitic matrix of more sodic plagioclase ($An_{93.7-91.5}Ab_{8.2-5.9}Or_{0.4-0.2}$; ~100 μm in long axis), more magnesian pyroxene ($En_{79-70}Wo_{16-10}$; < 10 μm size), and residual mesostasis. R2 consists of relict plagioclase ($An_{96.8-94.4}Ab_{5.3-3.1}Or_{0.3-0.1}$) with Na-rich overgrowth ($An_{94.6-92.1}Ab_{7.3-5.2}Or_{0.7-0.1}$) in an aphanitic matrix of plagioclase ($An_{94.4-92.2}Ab_{7.4-5.3}Or_{0.5-0.2}$; ~100 μm long), olivine (Fo_{84-80}; <10 μm size), and residual mesostasis. R3 consists of relict plagioclase ($An_{96.5-94.7}Ab_{5.0-3.3}Or_{0.3-0.1}$) with Na-rich overgrowth ($An_{89.1-86.4}Ab_{12.6-10.2}Or_{1.1-0.8}$) and four grains of relict olivine (Fo_{93-91}). R3 has the largest fraction of olivine grains (26.3 %) in the three regions. The matrix is composed of plagioclase ($An_{91.2-84.7}Ab_{13.9-8.2}Or_{1.4-0.6}$), interstitial olivine (Fo_{87-75}), a minor amount of pyroxene, and residual mesostasis.

Clast 2 (,66) can be divided into an optically dark and an optically bright region, R1 and R2, respectively. Both regions contain tiny droplets of a Fe-Ni metal-troilite-schreibersite mixture (<25 μm size). Fe-Ni metal has a meteoritic composition (Ni=3.3-4.7 wt.% and Co=0.3-0.4 wt.%). The dark region, R1, contains relict plagioclase ($An_{95.7-93.8}Ab_{5.9-4.1}Or_{0.4-0.1}$) with Na-rich rims ($An_{87.9-86.7}Ab_{12.6-11.3}Or_{0.9-0.7}$) and a crystallized melt of plagioclase ($An_{89.3-84.9}Ab_{14.0-10.0}Or_{1.1-0.7}$), olivine ($Fo_{83-81}$; ~30 μm long), and interstitial microcrystalline pyroxene. The bright region, R2, has relict plagioclase ($An_{96.3-94.8}Ab_{5.0.-3.6}Or_{0.3-0.2}$) with Na-rich rims ($An_{83.2}Ab_{15.8}Or_{1.0}$), relict pyroxene ($En_{76}Wo_{10}$; ~30 μm size), and a crystallized melt of plagioclase ($An_{86.4-82.1}Ab_{15.8-12.7}Or_{2.9-0.8}$) and fine-grained pyroxene ($En_{70-52}Wo_{29-11}$; <10 μm size).

Bulk major element compositions: Due to the small size of the melt clasts, we estimated bulk major element compositions from averages of (>200) defocused beam (20 μm) EPMA. Five regions from the two impact melt clasts can be divided into three chemical groups of high-K, low-K and intermediate compositions (Figure 1). Clast 1 R3 has high K (K_2O=0.72 wt.%) and P (P_2O_5=0.35 wt.%) and low Al (Al_2O_3=20.7 wt.%) and Ca (CaO=12.0 wt.%). On the other hand, Clast 1 R1 and R2 have low K (K_2O=0.31-0.27 wt.%) and P (P_2O_5=0.08-0.07 wt.%) with high Al (Al_2O_3=26.1-25.2 wt.%) and Ca (CaO=14.5-14.0 wt.%). Clast 2, in both dark and bright regions, has an intermediate composition between high-K and low-K melts (e.g. K_2O=~0.46, P_2O_5=~0.16 wt.%, Al_2O_3=~22.9 wt.%, CaO=~12.8 wt.%). The bulk Mg# of the 5 regions are similar (Mg#=80-78).

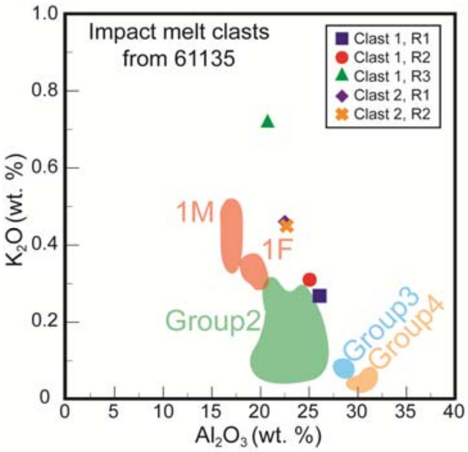

Figure 1. Al_2O_3 vs. K_2O (DBA data) for 5 regions from 2 clasts in 61135.

Discussion: *Origins of impact melt clasts in 61135:* Figure 1 indicates Clast 1 contains two different types of impact melt, high-K (R3) and low-K (R1 and R2), which are also distinguishable with their relict mineral compositions. The two melt components of Clast 2 have the same intermediate compositions (Fig. 1) with few relict minerals and might be created by mixing of high-K and low-K melts.

If the melts in the two clasts are related, there are two possible origins: (1) A single impact event hit a complex lithological target and incompletely mixed the melts, to produce high-K, intermediate-K, and low-K melt fractions. (2) An impact produced either a high- or low-K melt. A second impact produced a melt at the other end of the K spectrum. The melts in Clast 1 represent those two end member melts. If the second impact melt digested older fragments of the first impact melt, then that may have produced the intermediate compositions of Clast 2. Alternatively, the melts are not related and require three or more impact events.

Comparison with 9 other impact melt clasts from 60016 and 65095: To clarify the origins of impact melt clasts, we plot the Mg# of relict mafic minerals against bulk Al_2O_3 (Figure 2) for the 61135 melts described here and other Apollo 16 melts in our study. The plot confirms the conclusion made above that two target lithologies are required for the melts from 61135 Clast 1. There is no relict data from 61135 Clast 2, so it does not appear in the figure. The data in Fig. 2 also indicate that at least 4 different target regions are required to produce the 6 melt clasts in 60016 [11]. Three clasts from 65095 have similar mineral and bulk compositions, implying the same origin, but are different from clasts from 60016 [12]. The melt clasts in 61135 require at least one other distinct impact in addition to those for melt clasts in 60016 and 65095.

We obtained Ar-Ar shock retention ages for 6 impact melt clasts from 60016 [11]. We find evidence for at least 5 different impact events clustered within short span of 4.0-3.7 Ga for 6 clasts from 60016, which could not have been derived from single (Imbrium) event. The data here suggest that Ar-Ar ages for clasts from 65095 and 61135 may be distinct from those of clasts from 60016. However, a recent thermal disturbance of the K-Ar system means that the formation age of the one 65095 clast analyzed so far cannot be determined precisely enough to compare. Analyses of siderophile elements in some of these clasts also point to multiple impact events [14]

Conclusion: From the combined results from relict mineral compositions and bulk compositions, 11 melt clasts require at least 6 individual target regions. Ar-Ar ages confirm that clasts from 60016 originated from at least 5 distinct impact events. Thus, several impact events occurred in or near the PKT region and were not produced by a single (i.e., Imbrium) impact event.

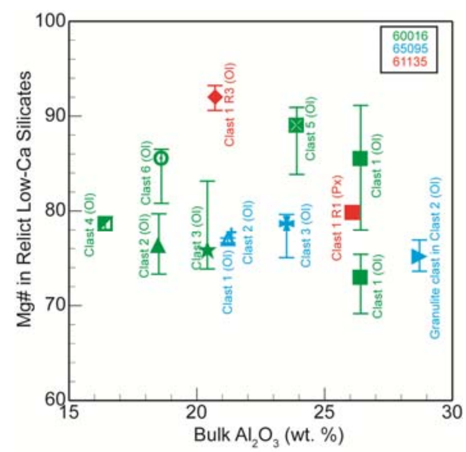

Figure 2. Al_2O_3 (DBA) vs. averaged Mg# (in relict low-Ca silicates) for impact melt clasts from 60016, 65095 and 61135. Bars indicate range of Mg#.

References: [1] Papanastassiou D.A. and Wasserburg G.J., 1971. *EPSL* **11**. 37-62. [2] Turner G et al., 1973. *Proc. LPSC* **4**. 1889-1914. [3] Tera F et al., 1974. *EPSL* **22**, 1-21. [4] Ryder G., 1990. *EOS. Trans. Am. Geophys. Union* **71**. 313-323. [5] Haskin L.A. et al., 1973. *Proc. LPSC* **3**, 1275-1296. [6] Hartmann W.K., 2003. *MAPS* **38**, 579-593. [7] Cassata W.S. et al., 2011. *GCA* **74**, 6900-6920. [8] Fernandes V.A. et al., *MAPS* **35**. 1355-1364. [9] Norman M.D. et al., 2006 *GCA*. **70**, 6032-6049. [10] Korotev R.L., 1994. *GCA* **58**, 3931-3969. [11] Niihara T. et al., 2012. *GCA*, submitted. [12] Niihara T. and Kring D.A., 2012 *MAPS* **47**, Suppl. #5074. [13] Joy K. H. et al., 2011 *GCA* **75**. 7028-7225. [14] Liu et al., 2013 *LPSC*, this volume.