BADDELEYITE CHRONOLOGY OF NORTHWEST AFRICA 6950: A 3.1 Ga LUNAR OLIVINE GABBRO PAIRED WITH NWA 2977 AND THE CUMULATE MARE GABBRO LITHOLOGY IN NWA 773.

B. J. Shaulis[1], M. Righter[1], T. J. Lapen[1], R. L. Korotev[2], A. J. Irving[3], S. M. Kuehner[3]. [1]Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas 77204-5007 (bshaulis@uh.edu), [2]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, [3]Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195.

Introduction: NWA 6950 is a gabbroic lunar meteorite collected from the Northwest African desert allegedly in Mali near the border with Algeria. The meteorite is a single yellow-green stone with a partial fusion crust and, along with 7 other fragments that fit together into a single piece, weights a total of 1649 g. Small veins of black shock-induced melt can be seen in the interior of the meteorite. The bulk composition of NWA 6950 suggests it is closely related to the NWA 773 clan of meteorites, a group of paired and/or petrographically related stones which includes: NWA 773, NWA 2700, NWA 2727, NWA 2977, NWA 3160, NWA 3333, and Anoual [1-3]. New U-Pb and ^{207}Pb-^{206}Pb ages of baddeleyite in NWA 6950 confirm petrogenetic linkages with olivine gabbro in NWA 2977.

Analytical Methods: For instrumental neutron activation analysis, we analyzed 6 subsamples of 18–25 mg in mass [4].

In Situ dating of baddeleyite was conducted by LA-ICPMS at the University of Houston using a Varian *810* quadrupole mass spectrometer coupled with a PhotonMachines *Analyte.193* excimer laser ablation system. The laser ablation was performed using a 12μm dia. laser spot size with a 6Hz repetition rate over 20s and a fluence of 3 J/cm^2. The Phalaborwa baddeleyite standard (2059.2 Ma[5]) was used as the external calibration standard and baddeleyite in FC5z (1099 Ma[6]) as the internal standard. Data reduction followed methods outlined in [7].

Petrography and Mineral Chemistry: The gabbro is relatively coarse grained with a cumulate igneous texture. The major phases are cumulate olivine ($Fa_{31.9-32.7}$, Fe/Mn=85-97), low-Ca pyroxene ($Fs_{27.1-28.1}Wo_{4.8-4.5}$, Fe/Mn=47-55), pigeonite ($Fs_{25.6}Wo_{9.2-11.1}$, Fe/Mn=47-52), and subcalcic augite ($Fs_{13.9}Wo_{36.9}$, Fe/Mn=41), with interstitial calcic plagioclase ($An_{87.9-93.0}Or_{1.1-0.9}$). Accessory minerals are ilmenite, Ti-chromite, armalcolite, troilite, baddeleyite, taenite and merrillite with rare zirconolite and K-feldspar.

U-Pb and Pb-Pb results: A total of 7 analyses were performed on four baddeleyite grains from a single section of NWA 6950 (Fig. 1). Most baddeleyite grains were <50 μm in the longest dimension. The following ^{207}Pb-^{206}Pb ages were obtained: Baddeleyite **A** yielded ages of 3100±45 Ma and 3138±45 Ma (All uncertainties are presented at the 2σ level). Baddeleyite

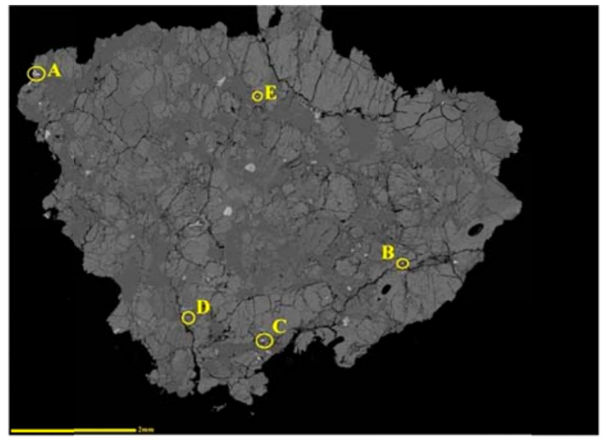

Figure 1: BSE image of NWA 6950. Yellow circles indicate the location of baddeleyite grains. Scale bar is 2 mm.

B yielded an age of 3098±38Ma. Baddeleyite **C** yielded ages of 3076±44Ma, 3109±42 Ma and 3090±43 Ma. Baddeleyite **E** yielded an age of 3088±43 Ma. Baddeleyite **D** was too small to analyze. The weighted average age (Fig 2.) of these 7 analyses is 3100±16 Ma. A U-Pb concordia age (Fig. 3) was also obtained with an upper intercept age of 3110±22 Ma. The normal and reverse discordance and modern lower intercept in Fig. 3 reflects residual instrumental fractionation of U and Pb after correction to internal standards. During LA-ICPMS analysis, the instrumental fractionation of U and Pb is found to be significantly greater in baddeleyite than zircon but

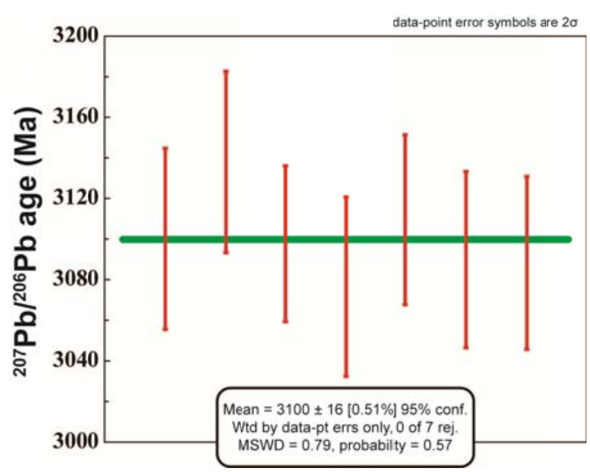

Figure 2: Weighted-average plot constructed using Isoplot v.3.5 of 7 analyses from 4 baddeleyite grains. Decay constants of [11].

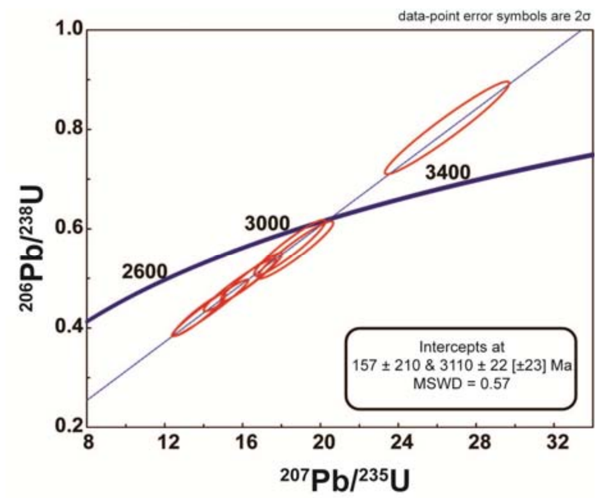

Figure 3: Concordia plot constructed using Isoplot v.3.5 of 7 baddeleyite analyses. The upper-intercept age of 3100±22 Ma (2σ) represents the crystallization age. The lower intercept at zero is a function of instrumental fractionation of U and Pb during LA-ICPMS analysis. Decay constants of [11].

fractionation of $^{207}Pb/^{206}Pb$ ratios is similarly very small. Importantly, the discordance is not a result of complex U-Pb isotope systematics in the baddeleyite and given that both the Pb-Pb and U-Pb ages are identical within uncertainty, we interpret these ages as reflecting the primary crystallization.

Bulk composition: NWA 6950 is indistinguishable in composition from other samples of the olivine gabbro cumulate lithology in NWA 773, NWA 2977, and NWA 3333 ([8], Fig. 4). The NWA 773 clan of meteorites is distinct in being rich in Co and poor in Na compared to other mafic lunar meteorites (Fig. 4) and mare basalts from the Apollo missions [9].

Discussion: The ^{207}Pb-^{206}Pb age of 3100±16 Ma and $^{206}Pb/^{238}U$ age of 3110±22 Ma are identical within error to a ^{207}Pb-^{206}Pb baddeleyite age of 3116±7 Ma [10] (data of [10] is recalculated with the U decay constants of [11]) and a Sm-Nd age of 3100±50 Ma [12] from NWA 2977. The U-Pb, Pb-Pb and Sm-Nd ages are 300-400 Ma older than the 2.7-2.8 Ga Ar-Ar ages found in NWA 773/2977/3160 [13,14]. The weighted average of U-Pb and Sm-Nd age data from NWA 2977 and 6950 is 3113±6 Ma and this age is the best estimate for the crystallization age of the olivine gabbro lithology in these meteorites. This age is among the youngest measured for lunar igneous rocks.

The 3113±6 Ma age of olivine gabbro in NWA 2977 and 6950 is ~100 Ma older than the 2993 ± 32 Ma Sm-Nd age for the olivine gabbro in NWA 773 [16] which is thought to be petrogenetically related to olivine gabbro in NWA 6950 and 2977. The age discrepancy is problematic given the chemical and petrographic similarities for olivine gabbro in the NWA 773 clan (e.g., Fig. 4). It could be possible that the gabbro in NWA 773 formed later, but by similar processes and source regions. Future isotope tracer studies will further test petrogenetic connections between samples.

Conclusions: The chronological and petrologic data for olivine gabbro in NWA 6950 and NWA 2977 are identical and confirm that they were likely petrogenetically related. The genetic relationship between olivine gabbro in NWA 6950 with olivine gabbro in other stones in the NWA 773 clan is likely, but further geochronologic and isotopic work is required to confirm this.

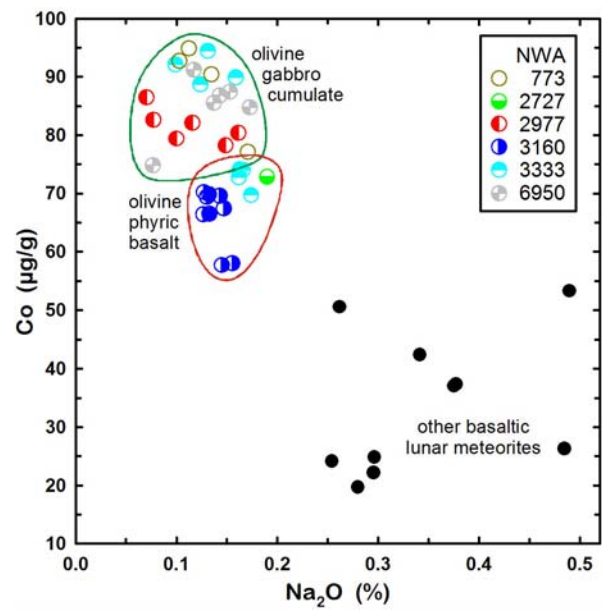

Figure 4: NWA 6950 lies in the field of other samples of the olivine gabbro cumulate among the NWA 773 clan of stones [15].

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References: [1] Bunch et al., (2006) *LPSC XXXVII* #1375, [2] Zeigler et al., (2006) *LPSC XXXVII* #1804, [3] Weisberg et al., (2008) Met. Bull. 94, *MAPS* 43, 1551-1588. [4] Korotev et al. (2009) *M&PS*, 44, 1287–1322. [5] Heaman et al., (2009) *Chem. Geol.*, 261, 43-52. [6] Paces and Miller, (1993) *JGR*, 98, B8, 13997-14018. [7] Shaulis et al., (2010) G^3, 11, Q0AA11. [8] Kuehner et al., *this conf.* [9] Jolliff et al. (2003) *GCA*, 67, 4857–4879. [10] Zhang et al., (2011) *MAPS*, 45, 1929-1947. [11] Schoene et al., (2006), *GCA*, 70, 426-445. [12] Nyquist et al., (2009) *MAPS*, 44, A159. [13] Burgess et al., (2007), *LPSC XXXVIII* #1603. [14] Fernandes et al., (2003), *MAPS*, 38, 555-564. [15] Jolliff et al., (2007) *LPSC XXXVIII* #1489. [16] Borg et al., (2009) *GCA*, 73, 3963-3980.