U-PB AGES AND CHEMICAL COMPOSITIONS OF APOLLO 11 REGOLITH GLASSES. M. D. Norman[1], T. R. Ireland[1] and L. Cousins[1], [1]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia (marc.norman@anu.edu.au).

Introduction: Lunar regolith glasses carry important information about the impact and volcanic history of the Moon, and the composition of the lunar crust. We report major and trace element compositions and U-Pb isotopic data for a suite of volcanic and impact glasses separated from regolith that was collected at the Apollo 11 landing site. The aim of this study is to investigate the ages and origins of these glasses.

Samples and Methods: Petrographic characteristics of ~700 particles in the 25-250 µm size range separated from a 2g aliquot of regolith sample 10084 were examined by optical and electron microscopy. About half of these particles were heterogeneous with either undigested clasts or variations in backscatter response indicating chemical heterogeneities; these particles were not studied further. The remaining 422 particles were clean glass. Major element compositions of these glasses were measured by electron microprobe. U-Th-Pb isotopic compositions and trace element abundances were measured on a subset of 50 of these particles by SHRIMP ion microprobe and laser ablation ICPMS, respectively. Major element compositions were normalized to the VG-2 glass to correct for instrument drift. The BCR-2G and BHVO-2G glasses were used to calibrate the isotopic and trace element data.

Results: The glasses were classified into highlands, mare, and picritic compositions based on their CaO/Al_2O_3 vs. MgO/Al_2O_3 following the scheme of Zeigler et al [1] (Fig. 1). ~10% of the glasses were classified as having a highlands composition (CaO/Al_2O_3 ≤0.75). Mare (CaO/Al_2O_3 >0.75, MgO/Al_2O_3 <1.25) and picritic (CaO/Al_2O_3 >0.75, MgO/Al_2O_3 >1.25) compositions were subequal in abundance. Highlands glasses have 15-30 wt% Al_2O_3 and 0.4-7.1 wt% TiO_2, with strong anti-correlations of Al_2O_3 with TiO2 and Ca/Al as well as FeO. Glasses classified as 'mare' have 0.6-13.6 wt% TiO_2, with a mode at ~6-9 wt%. Major element compositions of the mare glasses overlap with those of the local mare basalts at predominantly CaO/Al_2O_3 >0.9, and with the size fractions of the local regolith at lower CaO/Al_2O_3 (0.78-0.95). Glasses classified as picritic include some VLT compositions with TiO_2 as low as 0.4 wt%, but most are strongly clustered between 9-12 wt% TiO_2. Picritic glasses have systematically higher FeO at a given TiO_2 than the mare glasses.

The subset of glasses analyzed for U-Th-Pb and trace element compositions were selected based on the major element data to represent highlands compositions and mare compositions similar to the local regolith on the assumption that these would likely represent impact-produced glasses and therefore provide information on the local impact flux. We also analyzed examples of the main group of picritic glasses on the assumption that these would likely be volcanic and therefore provide information about the magmatic history of the site. The trace element and isotopic data will help to refine the petrogenetic interpretations of these glasses.

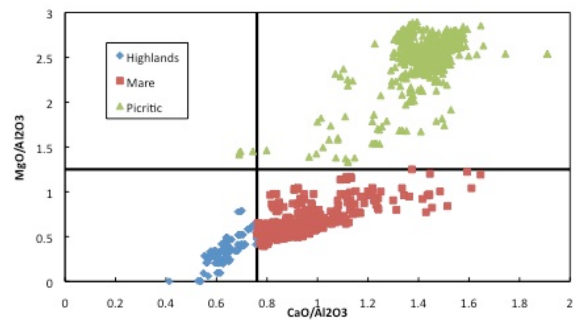

Fig. 1. CaO/Al_2O_3 vs. MgO/Al_2O_3 compositions of Apollo 11 regolith glasses illustrating the compositional classification of the glasses.

Trace elements. The highlands glasses are enriched in LREE/HREE with La ranging from 12 to 146 x CI. Th concentrations range from 0.4-5.7 ppm, with a wide range of Th/U (1.5-13.1) that is positively correlated with incompatible element concentrations. The mare and picritic glasses have flat to LREE-depleted patterns and negative Eu anomalies. La contents of the mare glasses range from 30-120 x CI. Th concentrations range from 0.9-3.9 ppm with Th/U ranging from 3.6 to 8.7, again with a broad positive correlation of Th/U with incompatible element content. The main group of picritic glasses with TiO_2 = 9.7-12.3 wt% has a more restricted set of trace element compositions with La = 25.8 to 28.5 x CI, Th = 0.35 to 0.42 ppm, and Th/U = 3.0 to 3.7.

U-Pb isotopic compositions. The main group of picritic glasses has relatively narrow ranges of $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$, consistent with their major and trace element characteristics. Twelve of the 15 particles have $^{207}Pb/^{206}Pb$ ages ranging from 3569 $\pm$ 117 Ma to 3906 $\pm$ 91 Ma, producing a weighted mean age of 3768 $\pm$ 47 Ma which is similar to that of the low-K Apollo 11 mare basalts [2]. Unfortunately, the SHRIMP analyses appear to be complicated by possible matrix effects that result in unrealistically old $^{206}Pb/^{238}U$ ages of these glasses (≥5 Ga) when calibrated against the USGS glasses directly. Adjusting the U+UO data for the regolith glasses against the concentrations measured by LA-ICPMS on the same grains produces more reasonable results with a weighted mean $^{206}Pb/^{238}U$ age of 3776 ± 95 Ma (n = 10) for the picritic glasses, identical to the $^{207}Pb/^{206}Pb$ results. Although additional development of the analytical method is clearly required, these results are encouraging.

In contrast, the highlands and mare glasses show much greater diversity in their apparent ages, and greater differences in their $^{207}Pb/^{206}Pb$ vs. $^{206}Pb/^{238}U$ ages. The apparent $^{206}Pb/^{238}U$ ages for the highlands glasses ranges from 34 ± 9 to 544 ± 68 Ma, whereas their apparent $^{207}Pb/^{206}Pb$ ages are 2140 to 4450 Ma. The mare glasses show a similar pattern with apparent $^{206}Pb/^{238}U$ ages ranging from 40 to 4000 Ma vs. $^{207}Pb/^{206}Pb$ ages of ~2-4 Ga. Similar relationships have been observed in Apollo 17 regolith glasses [3].

Discussion: The tight clustering of the major element, trace element, and U-Pb isotopic compositions of the picritic glasses are consistent with a volcanic origin of these glasses, probably in a single eruptive event. The U-Pb data suggest this eruption occurred at about the same time as emplacement of the crystalline mare lavas that were sampled by Apollo 11.

The highlands glasses are almost certainly of impact origin. Compositional trends of these glasses are consistent with mixing between highly feldspathic (≥ 30 wt% Al_2O_3) crust and high-Ti basalt compositions. The most feldspathic glasses that we analyzed have Ti/Sm of 2700-4050 and Mg# of 0.6-0.7, which would be more consistent with ferroan anorthositic lithologies rather than Mg-suite cumulates in the crust sampled by these highlands glasses [4]. Although more data are needed, a predominantly ferroan anorthositic crust in the vicinity of the Apollo 11 landing site would suggest a crustal composition similar to that observed at Apollo 16, and contrast with the predominance of Mg-suite crustal rocks around the Apollo 17 site [3].

The mare glasses studied here appear to be predominantly of impact origin based on their broad range of compositions, the compositional similarity of many of these glasses to the local regolith, and the predominance of relatively young $^{206}Pb/^{238}U$ ages. Additional work is necessary to evaluate the possibility that a significant proportion of the mare glasses may be of volcanic origin, or formed by impacts into the crystalline mare lavas rather than the local regolith.

Accurately dating lunar regolith glasses remains analytical challenging. The application of U-Pb isotopic compositions for this assumes that Pb is lost as a volatile element during both impact and volcanic glass-forming events. This appears to be a reasonable assumption for many volcanic glasses but the discrepancy between $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ compositions observed for the impact glasses suggests that some of them may retain a substantial fraction of Pb inherited from the pre-impact target. Incorporation of a modest amount of Pb into the glasses during their residence in the lunar regolith may also affect their compositions.

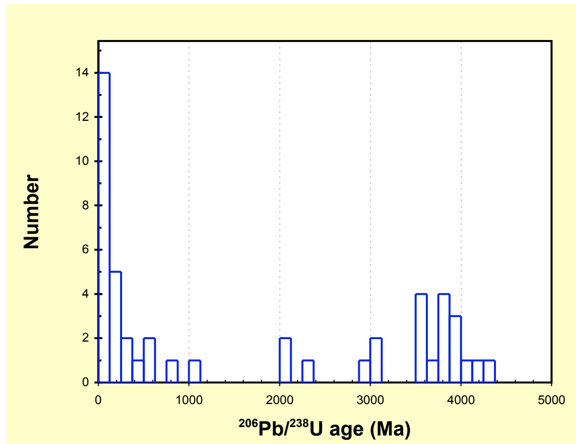

Fig. 2. Frequency distribution of $^{206}Pb/^{238}U$ ages for regolith glasses from 10084. The older population with ages of 3.5-4.0 Ga is dominated by picritic glasses, which are probably volcanic in origin,. The younger glasses with ages <1 Ga are either highlands or mare glasses that probably formed by impacts. The abundance of impact glasses with apparent ages of ≤500 Ma has been observed at other landing sites [3] and appears to be a common feature of lunar regolith glasses.

An abundance of relatively young ages in lunar impact glasses (Fig. 2) has now been observed at several landing sites and appears to be a general feature of regolith glasses. A significant question is whether this reflects a genuine increase in the impact flux or the depth-time scales of regolith mixing processes. The broadly similar age distributions that have been obtained from regolith glasses collected in diverse geological settings may indicate the former, although additional modeling is needed to address the problem more directly.

References: [1] Zeigler R. A., Korotev R. L., Jolliff B. L., Haskin L. A., and Floss C. (2006) *GCA* 70, 6050-6067. [2] Snyder G. A. et al. (1994) *GCA* 58, 4795-4808. [3] Norman M. D., Adena K. J. D. and Christy A. G. (2012) *Australian J. Earth Sci.* 59, 291-306. [4] Norman M. D. and Ryder G. (1980) PLPSC 11, 317-331.