A NEW APPROACH TO DATING LUNAR SPHERULES USING U-TH-PB CHEMICAL AGES. M. D. Norman[1], N. E. B. Zellner[2], and K. Adena[1], [1]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia (marc.norman@anu.edu.au), [2]Department of Physics, Albion College, Albion, MI 49224 USA (nzellner@albion.edu).

Introduction: The lunar regolith contains thousands of spherules of quenched impact melt and pyroclastic basaltic glass, providing a potentially powerful resource for understanding the impact and volcanic history of the Moon. We have developed a new technique for dating individual regolith spherules based on their U-Th-Pb concentrations measured by LA-ICPMS. This approach provides a relatively rapid way to establish the age distributions of a large number of spherules and can be applied to both volcanic and impact glasses. Data for Apollo 15 and 17 impact spherules suggest that young impacts dominate the age distribution but verification of the approach using more conventional techniques is required.

Samples and Methods: Glassy spherules were separated from size fractions of regolith samples 78481 (75-250 μm) and 15221 (≥150 μm) and polished in epoxy or crystalbond mounts. Major elements were measured by EMP or EDS-SEM. Trace element concentrations and Pb isotope data were collected by laser ablation ICPMS. Total Pb concentrations were calculated by summing the intensity data for masses ^{206}Pb, ^{207}Pb and ^{208}Pb. Additional details of the analytical methods are given by [1]. For the chemical age model, total Th+U concentrations were partitioned into Th and U assuming a lunar crustal value of Th/U=3.7 [2], converted to atomic abundances of ^{238}U, ^{235}U, and ^{232}Th, and corrected for decay of the parent isotopes to a series of time steps. Abundances of the radiogenic Pb isotopes were then calculated, summed, and converted to ppm concentrations for comparison with the measured compositions of the lunar spherules.

Results: Spherules were classified initially as volcanic mare or impact based on their shape, internal textures, and major element compositions [1]. *Major element compositions* of the spherules demonstrate a distinct regionality. The 78481 mare spherules have predominantly high-Ti compositions similar to the 74220 orange glass, with a minor VLT component (Fig. 1). In contrast the 15221 mare spherules are predominantly VLT similar to the Apollo 15 green glass, with a smaller number of particles having a low-Ti mare composition (Fig. 1). Impact glasses from both sites span a broad range of compositions that extend from the local mare compositions (i.e. high-Ti for 78481, VLT to low-Ti for 15221) to what appears to be a common highlands crustal composition with ~25-28 wt% Al_2O_3 (Fig. 1).

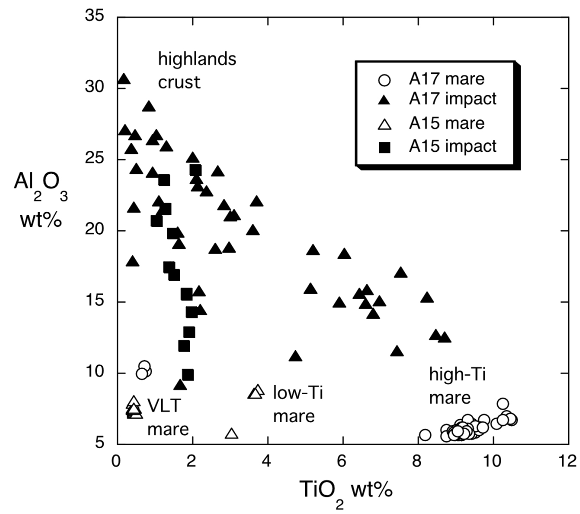

Fig. 1. Plot of Al_2O_3 vs TiO_2 wt% for 78481 and 15221 regolith spherules.

Trace element compositions also distinguish the impact spherule provenance, with the 15221 spherules having systematically higher incompatible element contents compared to those from 78481, suggesting a larger exposure of near-surface KREEP in the Apollo 15 impact source regions (Fig. 2). Compared to the highlands impact glasses, mare glasses from both of the sites have considerably lower concentrations of U+Th and other incompatible element (Fig. 3)

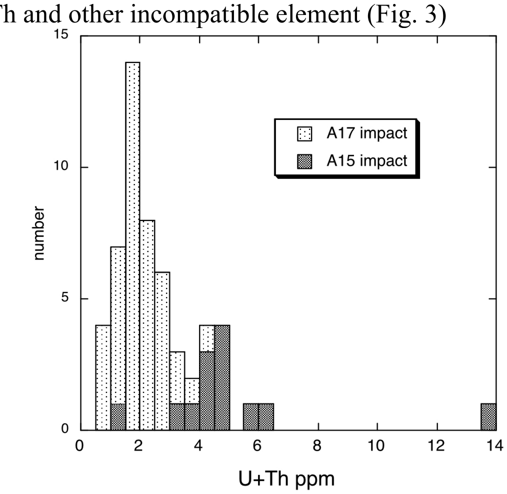

Fig. 2. Histogram of U+Th contents of impact spherules from 78481 and 15221.

Chemical ages. Fig. 3 shows the total Pb concentrations of the 15221 and 78481 spherules plotted against their U+Th contents. Mare spherules (inferred to be predominantly volcanic) form tight clusters with the Apollo 15 glasses distinguished from the Apollo 17 spherules by their lower U+Th and Pb contents. The 15221 mare spherules appear to be somewhat younger than those from 78481 (Fig. 3), and the inferred ages of these groups are broadly consistent with previously established eruption ages of the Apollo 15 green glass and Apollo 17 orange glass [3].

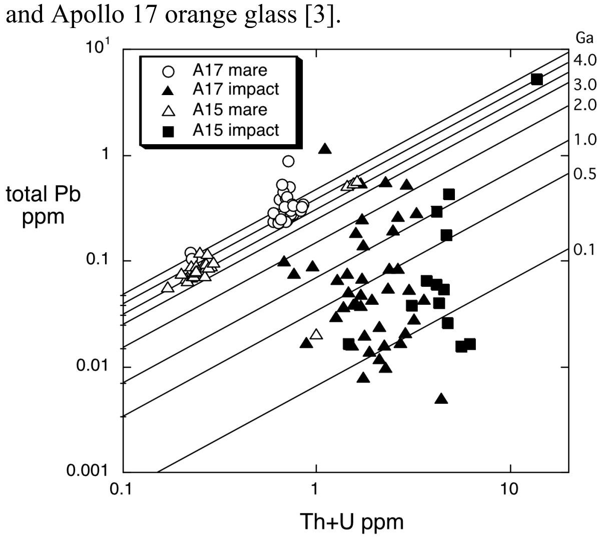

Fig. 3. Total Pb concentrations of 15221 and 78481 spherules plotted vs. their U+Th contents. Lines are isochrons of constant age (Ga).

In contrast, the impact glasses tend to have systematically lower Pb contents by up to 1-2 orders of magnitude compared to the mare spherules, despite having considerably higher U+Th contents. The clear implication of these data is that the impact spherules are considerably younger than the volcanic mare spherules. Impact ages inferred from the U-Th-Pb relationships are predominantly <2 Ga, with most of the impact glasses having apparent chemical ages of <500 Ma (Fig. 3). One of the low-Ti Apollo 15 mare spherules has anomalously low Pb for its U+Th and may be of impact origin, whereas the Apollo 15 spherule with the highest KREEP content (highest U+Th) has a chemical age of ~3.9 Ga, similar to igneous Apollo KREEP basalts [4], and therefore might be either impact or volcanic in origin.

Discussion: The U-Th-Pb chemical ages are model ages obtained by assuming that all of the Pb accumulated by radioactive decay of U+Th since the spherule formed. This model assumes that all previous Pb was lost from the spherule either by outgassing during volcanic eruptions or by thermal volatility during impact melting. Inheritance of any pre-existing Pb would mean the chemical ages are upper limits to the true formation age.

The tight clustering of mare glass ages according to their composition and provenance suggests that these assumptions are generally valid for lunar pyroclastic eruptions, and that Pb was outgassed as a volatile species along with other chalcophile elements during eruption. The occurrence of elevated Pb in some of the mare spherules, in particular those from 78481, resulting in unrealistically old ages (Fig. 3), suggests that outgassing was incomplete in some cases or that those spherules with anomalously old ages acquired additional Pb either during residence in the lunar regolith or during sample handling [1]. However, the tight clustering of U-Th-Pb compositions and realistic ages of the Apollo 15 and 17 volcanic spherules shows that over 3 billion years of residence in the regolith typically does not obscure the compositional characteristics of lunar glasses.

The predominance of young ages and local provenance of impact glasses implies production primarily in small craters, perhaps <1 km diameter [1]. The abundance of impact ages ≤ 500 Ma may imply that the Phanerozoic was a time of enhanced impact flux, which could have interesting implications for biological evolution and solar system dynamics. Argon ages of some chondrite groups also show a young peak [5] raising the possibility of a long-lived source of Earth-crossing impactors associated with collisions in the asteroid belt (a mini-cataclysm?). However, the role of gardening as a possible bias on the preservation of spherules in the near-surface regolith needs further clarification.

Chemical ages based on U-Th-Pb concentrations appear to be a promising approach for dating pyroclastic eruptions and impact events on the Moon. Analysis of individual spherules by LA-ICPMS provides a relatively rapid evaluation of the age structure of impact and volcanic glasses in the lunar regolith combined with detailed information on trace element compositions. Alternatively, more precise isotopic data may be possible using other techniques such as ion microprobe or thermal ionization mass spectrometry. A direct comparison of the chemical ages with more conventional age determinations (i.e., ^{40}Ar/^{39}Ar) is also necessary to verify the approach.

References: [1] Norman et al. (2012) *Australian. J. Earth Sci.*, in press. [2] Yamashita et al (2010) *Geophys. Res. Let. 37*, L10201, doi:10.1029/2010GL043061. [3] Meyer C. (2010) *The Lunar Sample Compendium*; samples 15425 and 74220. http://curator.jsc.nasa.gov/lunar/compendium.cfm. [4] Carlson R. W. and Lugmair G. W. (1979) *Earth Planet. Sci. Lett. 45*, 123-132. [5] Swindle et al. (2009) *Meteoritics & Planet. Sci., 44,* 747-762.