NanoSIMS Pb/Pb dating of tranquillityite in high-Ti lunar basalts: constraints on ages and duration of high-Ti volcanism on the Moon.
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Introduction: U-Th-Pb geochronology by ion microprobe was first carried out three decades ago [1-2] to date phosphates and Zr-rich minerals from lunar samples, but the limited mass resolution of the instrument could not fully resolve isobaric interferences on the Pb isotopes. Subsequent analytical advancements improved the accuracy and precision of *in-situ* Pb isotopic measurements. In majority of such cases, the *in-situ* U-Pb dating of lunar samples was focused on zircon (e.g., [3] and refs therein), which occurs in rock types mainly representing the lunar highlands [3], while it is rare in mare basalts in which Zr, as well as U and Th, are mostly hosted by baddeleyite, zirconolite and tranquillityite. This latter group of minerals can also yield precise and accurate Pb/Pb ages [4-9], and they occur widely in mare basalts collected at each Apollo landing site [e.g., 5]. However, their small dimensions often pose serious challenges to application of *in-situ* dating techniques.

We have exploited the high-spatial-resolution capabilities of the Cameca NanoSIMS 50 to carry out Pb/Pb analyses on tranquillityite in three high-Ti mare basalts. The obtained Pb/Pb ages are not only in good agreement with previously published ages for these samples but we are also able to constraint eruption ages of the various types of Apollo 11 and 17 basalts more tightly than before.

Samples and techniques: Pb/Pb dating was carried out on tranquillityite in Apollo 11 sample 10044 and Apollo 17 samples 75055 and 74255. All three samples are characterized by high-Ti and low-K contents [10-13]. BSE images and X-ray maps of the polished sections were obtained using a Quanta 3D dual beam FIBSEM at the Open University, UK, and Zr X-ray maps were used to locate Zr-bearing minerals. Pb/Pb analyses were carried out using a Cameca NanoSIMS 50 installed at the University of Rennes 1, France. A primary O^- beam with a current of 120-140 pA was focussed on the sample surface, producing a spot size of ~ 3 µm diameter. Isotopes of ^{204}Pb, ^{206}Pb and ^{207}Pb were analyzed with a static probe in the magnetic peak-switching mode, with counting times of 4 s for ^{206}Pb and 10 s for ^{204}Pb and ^{207}Pb.

Results: The $^{207}Pb^*/^{206}Pb^*$ ratios were corrected from initial Pb using the measured ^{204}Pb. In 10044, 9 analyses carried out on 5 grains defined a weighted mean $^{207}Pb^*/^{206}Pb^*$ age of 3713 ± 8 Ma (Fig. 1a). In 75055 and 74255, 11 and 6 analyses performed on 5 and 3 grains, resp., yielded weighted mean $^{207}Pb^*/^{206}Pb^*$ ages of 3769 ± 8 Ma (Fig. 1b) and 3736 ± 10 Ma (Fig. 1c), resp.

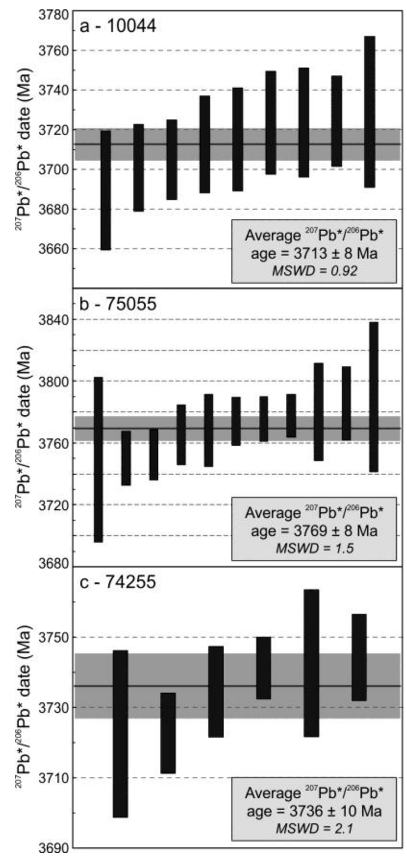

Fig. 1: Weighted mean $^{207}Pb^*/^{206}Pb^*$ ages for tranquillityite in high-Ti mare basalts 10044 (a), 75055 (b) and 74255 (c).

Accuracy of the tranquillityite Pb/Pb ages: To ensure that the tranquillityite Pb/Pb data accurately date the crystallization of the basalts, the Pb/Pb ages can be compared with previous age determinations carried out using different chronometers. Sample 10044 yielded a Rb-Sr isochron age of 3694 ± 68 Ma [14] and Ar/Ar whole-rock plateau ages of 3.73 ± 0.05 Ga and 3.71 ± 0.04 Ga [15-16]. The tranquillityite Pb/Pb age of 3713 ± 8 Ma is in good agreement with these ages. In sample 75055, the Pb/Pb age of 3769 ± 8 Ma is consistent with the Rb-Sr isochron age of 3752 ± 60 Ma [17] and with the well defined plagioclase

Ar/Ar age of 3.78 ± 0.04 Ga [18]. For sample 74255, two studies determined whole rock-mineral Rb-Sr isochron ages of 3751 ± 77 Ma [19] and 3694 ± 140 Ma [20], the latter being too imprecise to be useful in age comparisons in the present context. The Pb/Pb age of 3736 ± 10 Ma determined in 74255 is consistent with the Rb-Sr isochron age reported by [19].

Chronology of high-Ti volcanism at Apollo 11 and 17 landing sites: The tranquillityite Pb/Pb crystallization ages determined in this study have been compared with previous Pb/Pb, Rb-Sr and Sm-Nd ages determined on Apollo 11 and 17 basalts [references given in 21]. All Rb-Sr and Sm-Nd isochron ages have been recalculated using Isoplot [22] to ensure a thorough propagation of uncertainties. The revised decay constant for ^{87}Rb of 1.3968×10^{-11} yr^{-1} [23] has been used to recalculate Rb-Sr isochron ages.

At Apollo 11 landing site, basalts have been classified in five different types: A, B1, B2, B3 and D [11,24-25]. Types A, B1 and B2 have weighted mean ages that are statistically different. Type B2 basalts are the oldest, with a crystallization age of 3852 ± 65 Ma. Samples 10044 and 10047 belong to the B1 type and sampled the same lava flow [12]. Recent Pb/Pb analyses dated crystallization of 10047 at 3710 ± 4 Ma [5]. Our Pb/Pb dating of tranquillityite in 10044 yields an identical age of 3713 ± 8 Ma. Type B1 basalts thus define a very well constrained crystallization age of 3710 ± 4 Ma. Finally, Type A basalts are the youngest with a crystallization age of 3597 ± 20 Ma. These new ages compare well with those summarized in previous synthesis of [26-27], except that Type B2 is ~ 50 Ma older than considered in [27]. However, due to a relatively large uncertainty, the exact timing of Apollo 11 Type B2 volcanism remains uncertain.

Apollo 17 basalts have been grouped into Types A, B and C based on their whole rock chemistry [13]. Our Pb/Pb age of 3769 ± 8 Ma obtained for Type A sample 75055 is consistent with the weighted mean age of 3769 ± 30 Ma for Apollo 17 Type A basalts. Our Pb/Pb age thus define a tighter interval for crystallization of the Apollo 17 Type A lava flow at 3769 ± 8 Ma. Sample 74255 belongs to the Apollo 17 Type C basalts. Ages determined on this type yield a weighted mean age of 3755 ± 61 Ma, which is within error of the tranquillityite Pb/Pb age of 3736 ± 10 Ma. This is also in agreement with the less well-constrained crystallization age of 3750 ± 70 Ma for Type C basalts [27]. The combined dataset thus suggest that Apollo 17 Types A and C basalts have statistically different crystallization ages of 3769 ± 8 Ma and 3737 ± 9 Ma. Our new data also suggest that Type A Apollo 17 lavas erupted ~ 20 Ma earlier than estimated previously [27-28]. Apollo 17 Type B basalts may have been emplaced at 3719 ± 44 Ma. Unfortunately, the larger uncertainty on this age precludes any further assessment.

Conclusion: The Pb/Pb crystallization ages determined on tranquillityite in this study indicate that high-Ti mare basalts 10044, 75055 and 74255 were emplaced on the lunar surface at 3713 ± 8 Ma, 3769 ± 8 Ma and 3736 ± 10 Ma, respectively. These ages are consistent with previously determined ages but provide tighter constraints on the crystallization ages of three different types of high-Ti mare basalts. The high-spatial-resolution achieved in our dating protocol using the NanoSIMS 50 and the widespread occurrence of tranquillityite in lunar basalts have opened up a new avenue for carrying out rapid but accurate and precise age dating of mare basalts. Application of this technique to additional mare basalts has the potential to better constrain the emplacement ages of different basaltic units sampled during the Apollo missions. This will ultimately lead to the refinement of the lunar calibration curve used for crater counting studies, which is also critical for age estimations for other planetary bodies in the inner solar system.

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