New Ar-Ar Age Determinations for the Lunar Mare Basalts Asuka 881757 and Yamato 793169

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Introduction: There are relatively few basaltic lunar meteorites available for study (7-12 depending if breccias are considered) and yet they represent important samples to gain a global perspective of lunar volcanism. Considering that the previously determined Ar-Ar ages for the lunar meteorites Asuka 881757 (Asuka) and Yamato 793169 (Yamato) showed relatively large variation (Table 1), the present work is an attempt to better understand their ages as well as acquire other information from these basalts.

Samples: Yamato was found in the Minami-Yamato Nunataks Mountains, Antarctica and is crystalline subophitic basalt with Fe-rich pyroxene, plagioclase, and dark mesostasis (maskelynite). Pyroxene crystals are fractured and, together with the partly maskelynitized plagioclase, indicates that some degree of shock has been experienced by the meteorite, but that overall the texture is reported as not being disturbed [1]. The feldspars are very Ca-rich ranging from An_{88} to $An_{97.5}$, but mostly between An_{92} and An_{94} [2]; pyroxenes composition is variable ranging from $En_{1.9}$ to $En_{53.5}$, $Fs_{22.2}$ to $Fs_{84.3}$, and $Wo_{9.7}$ to $Wo_{40.7}$. Olivine is iron-rich at $Fa_{98.5}$ [2], in contrast to most other mare basalt olivines, which have compositions in the range of Fa_{20} to Fa_{70}. Asuka was found on the NE end of Nansen icefield, ~130 km S. of the Japanese Asuka station, Antarctica [3]. This meteorite is classified as a gabbroic mare basalt [3,4] and is much more coarsely grained than Yamato and typical mare samples. The pyroxenes are up to 4 mm across, and maskelynite and ilmenite up to 3 mm across. Plagioclase is typically 1.0 x 0.2 mm reflecting its subophitic texture [2,5]. Thin section descriptions have indicated that the sample consists of pyroxene and plagioclase being completely maskelynitized. Pyroxene is the dominant mineral with a composition ranging from $En_{7.8}$-$En_{43.6}$, $Fs_{30.7}$-$Fs_{68.2}$, and $Wo_{11.6}$-$Wo_{40.9}$. Also present are ilmenite, troilite, and traces of olivine (in symplectites, and iron-rich ranging from $Fa_{86.6}$ to $Fa_{94.6}$), apatite, silica phase (quartz), and nickel-iron [4]. The range of plagioclase is similar to that found in Yamato, An_{74} to An_{90} with a strong mode at approximately An_{90} to An_{95}. It shows similarities to Apollo 17 and Luna VLT basalts, which are also and supported by trace element data [6]. Although Asuka 881757 and Yamato 793169 have been paired, their mineralogy and bulk chemistry differ slightly. Plagioclase mineralogy indicates variance in the degree of shock history of the two meteorites; both appear to be low-Ti mare basalts but show some characteristics of high-Ti and VLT mare samples, in particular with respect to trace element concentrations such as Sc and Sm [6]. Based on mineralogical data, [1] showed that the crystallisation trends suggest that Yamato crystallised near the surface in disequilibrium growth condition, and that Asuka crystallised at depth under conditions closer to equilibrium condition, in similar lava unit.

Previous age determination: Summary in Table 1 (7,8). Age data for Yamato is questionable and no definitive formation age has been assigned to the sample. High $^{40}Ar^*/^{39}Ar$ temperature steps yield ages of greater than 3.9 Ga [7], Sm-Nd age data however, is 3.4 Ga [7]. Mineralogical studies have shown that the sample has been subject to a shock event that may have led to resetting of some of the isotopic systems. Glass is reported to be present in Yamato [9] but was not observed in the samples for this study (Yamato-793169, 58); $^{40}Ar^*/^{39}Ar$ age data [7] for the glass produced a total fusion age of 751 Ma that is thought to indicate the time of a major shock-event, which would account for the maskelynatized plagioclase. Asuka is also of great antiquity with a weighted mean age of 3.80±0.01 Ga [10]. Plagioclase mineralogy and stepwise heating data indicates that this meteorite has been subjected to lesser a degree of shock than Yamato. $^{40}Ar/^{39}Ar$ data has also shown that ^{39}Ar recoil has taken place with apparent ages in the first few steps representing only a small percentage of ^{39}Ar released with an age exceeding 4.0 Ga. Discordance in ages, found from different isotopic systems combined with the existence of maskelynitized plagioclase (and shock melt glass?), indicates that Asuka was disturbed by a post-crystallisation impact event [10]. Age data obtained prior to the present work suggest that Yamato is 3.9 to 4.3 Ga and Asuka is 3.81 Ga represent some of the older nearside mare basalts. Only the cryptomare are of this age group, these however, are chemically unlike Yamato and Asuka VLT basalts. [10] suggested that the only region that has age data close to the ancient age of Yamato is Mare Humboldtianum . The formation age of Asuka, measured by [10] is similar to those of some lunar mare basalts and lunar basin-forming events 3800-4000 Ma, and they suggest that this meteorite may have formed from a magma related to a basin forming event.

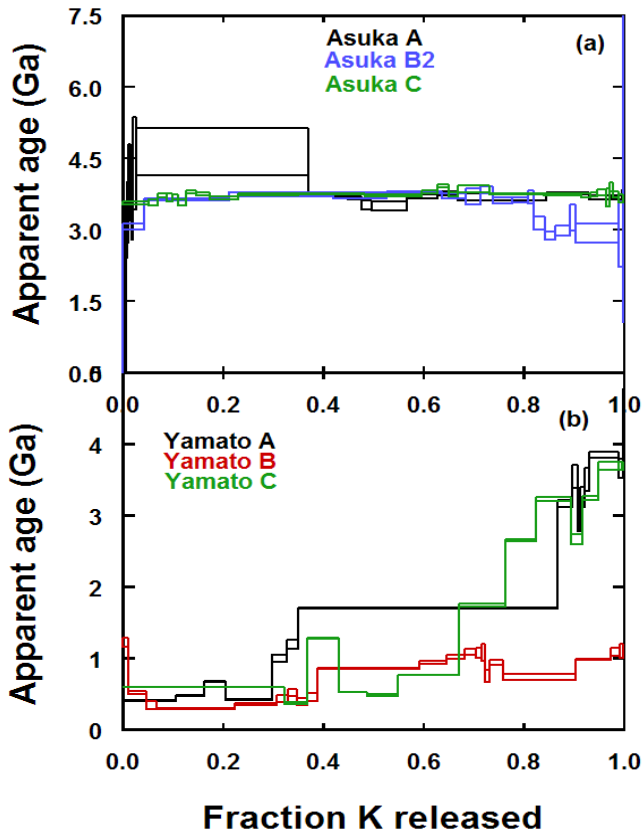
Method: The ^{40}Ar-^{39}Ar furnace step heating dating technique has been applied to four fragments of Asuka and three fragments of Yamato, in an attempt to determine the crystallisation age and timing of any shock events experience by the meteorites. Each of the fragments presented different contents of plagioclase and pyroxene, thus providing the possibility of extracting different geologic events depending on which phase was present with the larger amount: Yamato A (plagioclase, 1.7mg), B (pyroxene, 3.9mg) and C (mixed, 1.0 mg); Asuka A (plagioclase, 5.2mg), B1 (pyroxene, 4.2mg), B2 (pyroxene, 3.1mg), C (mixed, 3.4 mg).

Table 1 Summary of ages (in Ga) obtained using different isotopic systematics [7,8]
€High-temperature steps. £ impact event.

	^{40}Ar-^{39}Ar	^{204}Pb-^{206}Pb	Sm-Nd	^{87}Rb-^{87}Sr	^{232}Th-^{206}Pb	^{238}U-^{206}Pb	^{235}U-^{207}Pb	^{244}Pu-^{136}Xe
Y793169	3.9 – 4.3€ 0.751±0.004£	3.92±0.09	3.47±0.18	-	3.9-4.3	3.93±0.05	3.93±0.22	3.93±0.22
A881757	3.79±0.02 plag 3.81±0.02 glass	3.94±0.03	3.85±0.11	3.84±0.03	-	-	-	4.24±0.17

Results: Yamato data obtained for the three fragments analysed (Fig.1b) suggest that this meteorite has been disturbed 430 Ma ago, if not (or also) more recently at ~295 Ma, based on the lowest age obtained at low temperature steps. Spectra from Yamato A and C do not show any age plateau at intermediate and/or high temperatures. However, both of these fragments show maximum ages that are reasonably similar at 3.84±0.05 Ga and 3.69±0.06 Ga for A and C respectively. If only the last 13% of K released for fragment A is considered, then an age of 3.61±0.03 Ga is calculated, which is a comparable age to the maximum age of fragment C. The age spectrum for Yamato B does not show a steep increase in apparent age with temperature, rather there is a marked increase after 40% ^{39}Ar release to give relatively consistent ages corresponding to an age of 887±13 Ma (Fig. 1b). The likely explanation for this inconsistent age is the low ^{40}Ar content of this sample, which was 2.6 to 56 times lower than the other two fragments. This suggests that fragment B1 was mostly composed of shocked material, which lost part to all of its argon upon an impact event at 294±8 Ma. The age obtained at high temperature steps indicate partial degassing of more resistant phases such as pyroxene. Spectra for the Asuka fragments (Fig.1a) show relatively flat age spectra with ages of 3.68±0.01 (98% K), 3.68±0.02 (81% K), 3.81±0.01 (86% K) Ga for A, B2, and C respectively. The slope obtained by plotting the heating steps considered above on a ^{40}Ar/^{36}Ar vs. ^{39}Ar/^{36}Ar (not shown) show a narrower agreement in ages, 3.64±0.08 Ga, 3.62±0.06 Ga and 3.70±0.02 for A, B2 and C respectively.

Figure 1 (a) Asuka 881757 - Apparent age vs. K released during step heating; (b)Yamato 793169 - Apparent age vs. K released during step heating.



An age could not be determined for fragment Asuka B1 as, similar to Yamato B, this sample ^{40}Ar content was very low, and large errors were associated with it. Fragment B2 shows at high temperature a decrease in age suggesting ^{39}Ar-recoil at these steps. This effect had previously been reported for this meteorite by [10]. K/Cax1000 at high temperature steps (not shown) varies in Asuka from 0.13 to 1.73 for fragments A, B1 and B2; however fragment C shows a higher ratio of ~50. Yamato K/Cax1000 is comparatively higher with a range from 2.21 to 7.04.

Cosmic Exposure (CRE) ages for Yamato fragments shows a range of ages 8.8±0.3 Ma, 23.0±0.7 Ma and 18.1±1 Ma for fragment A, B and C respectively. The ^{38}Ar/^{36}Ar for the three fragments show trapped values of ~0.1869. The young CRE age for fragment A can be explained, similar to the ^{40}Ar-^{39}Ar age due to a disturbed system. For Asuka, the CRE age obtained are 3.4±0.1 Ma, 3.9±0.1 Ma, 6.7±0.2 and 9.8±0.3 Ma for fragments, A, B1, B2 and C respectively. The ^{38}Ar/^{36}Ar is similar to that observed in Yamato with exception to fragment C, which shows a strong influence of Cl in the sample (most likely terrestrial contamination). The variation observed in the CRE-ages for both Asuka and Yamato may be due to an improper use of ^{38}Ar production rate (presently it was used the nominal 1.4 x 10^{-8} cm^3 g^{-1} Ca Ma^{-1} [11]), or due to differences in the bulk composition of each fragment as a result of their small size versus the coarse texture of these meteorites.

Discussion and Summary: The age for lunar mare basalt Yamato 793169 is 3.71±0.11 Ga, and it was subjected to a major impact about 430 Ma. Similar age is obtained for Asuka 881757, 3.69±0.07 Ga, which is younger than previously determined [7] (Table 1), but neither of the three fragments analysed show disturbance at low temperature steps. Based on the chemical composition and age of Asuka 881757 and Yamato 793169 mare basalts, and comparing with lunar elemental composition maps by [12 and 13], and crater counting ages of mare flows on the lunar surface estimated by [14], the suggested sources four these meteorites are the SW rim of Mare Humorum, Lake Endymion (Mare Humboldtianum), and SW rim of Mare Australe. Yamato overall shows older CRE-ages than Asuka, thus supporting the idea that if these two meteorites are from the same lava, than Yamato should have been at a shallower depth than the Asuka. Also, because their Moon-Earth transition times are similar (Y=1.1 Ma and A=0.9 Ma, [15]), it is suggested that they were ejected from the Moon due to the same impact event, from different depths, and arrived in Antarctica at slightly different times.

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