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K-Ar ages and shock effects in lunar meteorites

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1. Introduction

The lunar crust and its dominant features formed during the first 700 Ma of our Solar System, thus covering a time not recorded by terrestrial rocks. This permits the determination of the lunar crater production rate - the most important chronological standard for dating planetary surfaces in the inner Solar System. The age of impact events on the lunar surface can be determined by measuring different isotopic systems in rocks. In contrast to ^{147}Sm/^{143}Nd and ^{87}Rb/^{87}Sr ages, which are used to date the solidification of the rock (e.g. basalt), the ^{40}Ar-^{39}Ar dating technique can also determine the resetting ages due to thermal events induced by impacts. These thermal/impact events can in some cases only cause partial Ar-loss (where only the low temperature argon release steps are affected). Therefore this dating technique can be applied to a broad range of rock types (i.e. not only impact melts). This is particularly relevant to the large number of lunar meteorites considered as more representative of the average lunar surface, compared to the Apollo and Luna mission samples which were limited to equatorial and nearside landing sites. Here we investigate on the influence of shock pressure and temperature on the ^{40}Ar budget of lunar basaltic meteorites.

2. Methods

A gabbro from Grass Valley, California, U.S.A., containing calcium-rich plagioclase (An_{94}) was experimentally shocked to pressures of 20, 24, 28 and 36 GPa. The shock reverberation experiments were carried out at the Ernst Mach Institute in Freiburg, Germany [1]. The recovered samples were studied macroscopically using optical microscopy and Raman spectroscopy. Argon ages were determined on irradiated samples by measuring the Ar released during step heating experiments. Partial and complete resetting of K-Ar system was determined by comparing these results with literature crystallization ages obtained by other isotopic chronometers: Sm/Nd, Pb/Pb, Th/Pb and U-Pb, (Tab. 1) [2-18].

3. Results

These are the firs mineralogical investigations on experimentally shocked rocks containing Ca-rich plagioclase with a composition relevant to lunar rocks. Plagioclase shocked to 1) 20 GPa shows undulatory extinction, 2) 24 GPa is almost completely isotropic, and 3) 28 and 36 GPa is completely transformed into maskelynite. Using the plagioclase with An_{94} as an experimentally calibrated barometer allows to determine the shock pressures recorded in lunar rocks (Table 1). The shock pressures are then compared with radiogenic ages.

3.1 Crystallisation and thermal events preserved in lunar basaltic meteorites

Asuka 881757, Yamato 793169 and MIL 05035 are thought to be paired based on similar chemistry and petrogenises. Crystallisation age obtained by Sm/Nd, Pb/Pb, Rb/Sr, Th/Pb, U/Pb and Ar/Ar [2] for Asuka 881757 is 3.846±0.080 Ga. This age is the same within error to that obtained using Ar/Ar, 3.726±0.063 Ga [3]. Previous crystallisation age obtained using Pb/Pb, Sm/Nd, Th/Pb, U-Pb and Ar/Ar [4] for Yamato 793169 is 3.858±0.098 Ga. Recent Ar/Ar work by [3] report an average on ages obtained on bulk and plagioclase of 3.751±0.085 Ga which is indistinguishable from those obtained be other systems. A younger age obtained for Yamato 793169 glass separates of 0.203 Ga suggests a more recent thermal event. Sm/Nd and Rb/Sr radiometric age determination for MIL 05035 by [5] suggest a crystallization age of 3.850±0.051 Ga which is indistinguishable from that obtained by Ar/Ar 3.878±0.046 Ga for two bulk samples [3]. These authors also reported that during argon release the low temperatures show a maximum age of a later thermal event at 1.638±0.098 Ga.

A crystallisation age for LAP 02205 of 2.980±0.036 Ga was determined using Ar/Ar, Sm/Nd, Rb/Sr and U/Pb [6-8]. This ages is the same as that obtained for Ar/Ar bulk analyses, 2.985±0.016 Ga [3 11].

Basaltic lunar meteorites NWA 2977 (olivine-rich cumulate gabbro) and NWA 3160 (fine-grained, olivine-phyric basalt with minor attached breccia matrix) belong to the NWA773 clan. Presently there is a Sm/Nd crystallization age of 3.10±0.05 Ga [9] for NWA 2977. The Ar/Ar analyses on bulk, pyroxene and plagioclase separates obtained by [10] suggest that the system has been disturbed likely by a thermal event at <2.6 Ga. For the breccia NWA

3160 there is currently only Ar/Ar data reported by [10] and suggest a disturbed system. Bulk and basalt samples show a complex release and a calculated age of ~2.65 Ga. The breccia on the other hand shows that the low temperature steps of the release pattern suggest a partial degassing at < 2.8 Ga, and at intermediate and high temperature there is an increase in apparent ages (~43% of the total ^{39}Ar-release) suggesting an age of 3.89±0.59 Ga.

Rb/Sr and Sm/Nd age reported for NWA 032/479 is 2.980±0.036 Ga [11], and [3] reported a slightly younger age at 2.917±0.059 Ga.

For NWA 4898 the reported crystallisation age was determined using Rb/Sr [12] and suggest an age of 3.600±0.059 Ga. This age is within error the same as that determined by Ar/Ar 3.536±0.020 Ga [13].

Similarly, for NWA 4734 there is only Ar/Ar age determination which shows a release spectrum suggesting to be affected by ^{39}Ar recoil. The total age calculated is 2.74±0.02 Ga. This age is indistinguishable from those obtained for NWA032/479 [14] and just slightly younger than the Ar age obtained or basalt LAP 02205 [3].

For Dhofar 287 a crystallisation age of 3.46±0.03 Ga was determined by [15]. Ar/Ar age reported by [16] is 3.136±0.086 Ga. U/Pb analyses determined by [17] on phosphates suggest an age of 3.34±0.20Ga which is intermediate between Sm/Nd and Ar/Ar ages.

Finally, radiometric ages for the basaltic breccia EET 96008 obtained using U/Pb ages on phosphates suggest an average age of 3.518±0.553 Ga [18]. Recent detailed Ar/Ar work on breccia, bulk and basalt fragments of the EET 96008 was able to discriminate different ages, 3.755±.342 Ga, 3.231±0.118 Ga and 2.650±.086 Ga [3], respectively. The bulk sample also suggests the maximum age for a more recent thermal event at 0.631±0.020 Ga.

4. Discussion

Preliminary investigation show that 1) formation of maskelynite, e.g. in Asuka 881757 is not leading to a loss of Ar, and even impact melt bearing samples (EET 96008) are not completely reset. In contrast partial or complete resetting of Ar ages were observed in some meteorites shocked to relatively low pressures, e.g. Yamato 793169 shocked to 21-25 GPa. This indicates that Ar loss is not a result of weak to moderate shock pressures. The partial or total resetting of a rock K-Ar age depends on elevated temperatures for extended periods of time, e.g. in a hot ejecta blanket.

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Table 1 Investigated lunar meteorites, including information on petrological type, shock metamorphic features, deduced shock pressures, and completely or partially reset Ar-ages.

Name	type	plag	shock pressure [GPa]	melt veins	reset Ar-age	partial loss
Asuka 881757	b	C	>25	Yes	No	No
Yamato 793169	b	B	21-25	Yes	No	Yes
MIL 05035	b	C	>25	No	No	Yes
LAP 02205	b	C	>25	Yes	No	No
NWA 032/479	b	n.d.	20-35	Yes	No	No
NWA 4898	b	C	>25	Yes	No	No
NWA 4734	b	B	21-25	No	No	No
Dhofar 287-A	b	C	>25	Yes	Yes	No
NWA 2977	b	B	21–25	Yes	Yes	Yes
NWA 3160	bb	B	21–25	Yes	n.d.	n.d.
EET 96008	bb	A-C	n.d.	n.d.	No	Yes

Type b = basalt, bb = basalt and breccia; shock features in plagioclase are: A = birefringent (i.e. plagioclase), B = partially isotropic, and C = completely isotropic (i.e. maskelynite); n.d.= not determined.