^{40}AR/^{39}AR AGES VS. SHOCK FEATURES IN APOLLO 16 AND 17 SAMPLES.

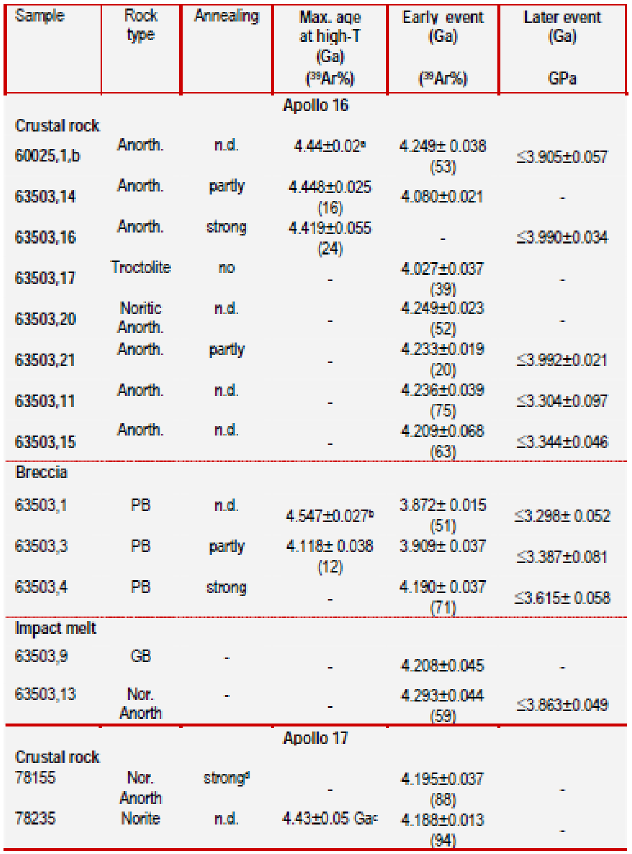
V. A. S. M. Fernandes[1] and J. P. Fritz[2],
[1]Physics Inst. Space Research & Planet. Sci., Univ. Bern, Sidlerstr. 5, 3012 Bern, Switzerland (veraafernandes@yahoo.com),
[2]Museum für Naturkunde, Leibniz Institut an der Humbold Universität zu Berlin. Invalidenstr. 43, 10115 Berlin, Germany.

Introduction: Both the lunar cataclysm theory and the continuous decline in impact events [1-5] prior to ~3.9 Ga are not well constrained, and thus there is a need of additional geochronometry to better define this early period. Samples that exist in the Apollo and Luna collections potentially record this history (not only impactites but also other rocks, e.g. highland rocks and basalts that have been affected by thermal regimes as a result of impact(s)), as well as impact melts in meteorites, and in the future, samples that will be collected from more and diverse lunar sites. Here we present petrographic and shock metamorphic studies of Apollo 16 and 17 rocks for which ^{40}Ar/^{39}Ar ages were reported in [6&7]. Samples 60025 (Apollo 16 landing site), 12 fragments from soil 63503 (station 13), and 78155 and 78235/78236 (both from Apollo 17 station 8) were studied to discriminate crystallisation and reset ages obtained by ^{40}Ar/^{39}Ar and encompassing a period from ~4.56 to ~3.3 Ga. Polished thick sections were investigated using the SEM, Raman spectroscopy, and when possible also optical microscopy. Furthemore, ^{40}Ar/^{39}Ar data obtained by the authors [6&7] are compared and compiled with literature data.

^{40}Ar-^{39}Ar ages summary: For samples 60025 and 78235, distinct crystallization and metamorphic ages were reported in the literature [8&9]. ^{40}Ar/^{39}Ar ages of the thermally annealed anorthositic norite polymict breccia 78155 were reported by [10]. Our recent work [6&7], reported step heating ^{40}Ar/^{39}Ar ages, that are indistiguishable to those reported previously for these rocks [2&9-11]. The ^{40}Ar/^{39}Ar ages presented in [6&7; Table 1] for 63503 soil fragments show a similar age distribution compared to the decay-constant corrected ages of [12]. The impact ages obtained from Apollo samples are not restricted to a brief period ~ 3.9 Ga but cover a period starting at least ~4.3 Ga and continuing to as recently as ~3.3 Ga (Table 1).

Petrology and shock features: A summary of ^{40}Ar/^{39}Ar step heating ages [6&7] and diagnostic petrographic features is presented in Table 1. The two Apollo 17 samples, 78155 (a thermally annealed anorthositic norite polymict breccia [13]) and 78235 (a heavily shocked norite cumulate [e.g. 14&15], with plagioclase almost completely converted to maskelynite, and a crystallisation age of 4.43±0.05 Ga [9], gave identical values to those reported by e.g. [2&9-11] suggestive of a reset event at ~4.2 Ga. Also, the widely studied Apollo 16 cataclastic anorthosite 60025 [e.g 16], with a crystallisation age of 4.44±0.02 Ga [8] also suggests an age reset at ~4.25 Ga. A set of 12 fragments from soil sample 63503 was also analysed by [6&7]. Using SEM, Raman spectroscopy, and in addition, several sample sections were thin enough so that it was possible to carry out polarized microscopy (Table 1). Based on petrography, samples were divided into three groups: 1) *crustal highland material* 63503,11, -,14, -,15, -,16, ,17, -,20 and -,21; 2) polymict feldspathic fragmental breccias 63503,1, 63503,3 and 63503,4; and 3) *impact melts* 63503, 9 and -,13. The crustal highland material ranged from troctolites, to cataclastic anorthosite and olivine bearing anorthosite. Samples 63503,-14 and -,17 appear unshocked, and weak shock effects (undulatory extinction) are displayed by plagioclase and pyroxene in the other five samples (<24 GPa; see also [19 & 20]). Signs of thermal annealing were observed only in the crustual highland rocks 63503,16 and -,21. The ^{40}Ar/^{39}Ar data for these crustal rocks suggest a common age at ~4.2 Ga for the high temperature steps and a partial resetting age either at 3.9-4.0 Ga or at 3.3 Ga. One of the samples (63503,16) actually suggests an older [relic] age of 4.42 Ga at the high temperature heating steps.

Table 1: Petrography, Shock metamorphism & ^{40}Ar/^{39}Ar ages (6&7).



Sample	Rock type	Annealing	Max. age at high-T (Ga) (^{39}Ar%)	Early event (Ga) (^{39}Ar%)	Later event (Ga) GPa
			Apollo 16		
Crustal rock					
60025,1,b	Anorth.	n.d.	4.44±0.02^{a}	4.249± 0.038 (53)	≤3.905±0.057
63503,14	Anorth.	partly	4.448±0.025 (16)	4.080±0.021	-
63503,16	Anorth.	strong	4.419±0.055 (24)	-	≤3.990±0.034
63503,17	Troctolite	no	-	4.027±0.037 (39)	-
63503,20	Noritic Anorth.	n.d.	-	4.249±0.023 (52)	-
63503,21	Anorth.	partly	-	4.233±0.019 (20)	≤3.992±0.021
63503,11	Anorth.	n.d.	-	4.236±0.039 (75)	≤3.304±0.097
63503,15	Anorth.	n.d.	-	4.209±0.068 (63)	≤3.344±0.046
Breccia					
63503,1	PB	n.d.	4.547±0.027^{b}	3.872± 0.015 (51)	≤3.298± 0.052
63503,3	PB	partly	4.118± 0.038 (12)	3.909± 0.037	≤3.387±0.081
63503,4	PB	strong	-	4.190± 0.037 (71)	≤3.615± 0.058
Impact melt					
63503,9	GB	-	-	4.208±0.045	-
63503,13	Nor. Anorth	-	-	4.293±0.044 (59)	≤3.863±0.049
			Apollo 17		
Crustal rock					
78155	Nor. Anorth	strong^{d}	-	4.195±0.037 (88)	-
78235	Norite	n.d.	4.43±0.05 Ga^{c}	4.188±0.013 (94)	-

PB=polymict breccia: GB=granulitic breccia; n.d.=not detected. ^{a}Sm/Nd age [8]. ^{b}Maximum apparent age: last step at high-temperature (i.e.minimum crystallisation age). ^{c}Sm/Nd age [9]. ^{d}[13]

The three *polymict breccias* include fragments of individual minerals and lithic clasts. The majority of the lithic clasts are partly to totally metamorphosed primary rocks or even breccias, and impact melt clasts. Some impact melt clasts in samples 63503,1 and 63503,3 contain μm-size FeNi particles. The degree of thermal annealing increases from fragment 63503,1 to 63503,4, with sample 63503,1 preserving a relic age of ~4.55 Ga at high-temperature during ^{40}Ar/^{39}Ar step heating measurements [6&7]. Intermediate and low temperature steps suggest cooling ages between 4.2 and 3.3 Ga.

Two *impact melt fragments* 63503,-9 and -,13 were analysed. 63503,9 is composed of angular to subrounded plagioclase fragments set in an interstitial and unequilibrated quenched melt that hosts a myriad of pores. The intersertal impact melt 63503,13 shows radial plagioclase laths cross-cutting each other, interstitial olivine and pyroxene and some vesicles. The texture is indicative of a quickly quenched melt, i.e. quenched during the transported to the Apollo 16 site. In contrast, the texture of 63503,13 indicates cooling in a melt sheet thicker than 5 m to allow formation of plagioclase crystals (see [17] & refs. therein). Thus, likely the melt was later emplaced in the vicinity of the Apollo 16 landing site. The ^{40}Ar/^{39}Ar ages for these two samples are ~4.2 Ga for 63503,9 and ~4.3 for 63503,13 (Table 1).

Discussion: The shock features in the Apollo 16 and 17 samples reported here show an overall low degree of shock pressures (0 to <24 GPa), nonetheless the K-Ar systematics are disturbed. For comparison ^{40}Ar/^{39}Ar ages of lunar basaltic meteorites subjected to higher shock pressures (i.e. plagioclase was completely transformed into maskelynite) were reported recently [18]. Nonetheless, these basalts showed an overall good agreement of their K-Ar clock with ages determined by more thermally resistant chronometers (e.g. Sm/Nd). In an effort to better understand the effects of shock on K-Ar system, [19&20] report shock experiments on a terrestrial gabbro with plagioclase composition of An$_{94}$, relevant for the typical lunar plagioclase compositional range. This study advocates for a "cold" and ductile mechanism for the transformation of plagioclase into maskelynite [19]. Therefore, the observed shock effects in the studied Apollo 16 and 17 samples are not sufficient to explain the differences between K-Ar ages with those determined by more thermally resistant chronometers (e.g. Sm/Nd). Hence, maskelynite (and likely other shock related features) per se is not a diagnostic feature for loss of argon.

The petrographic studies of Apollo 16 and 17 samples showed that sample 78155, and soil fragments 63503,-3, -,4, -,14, -,16 and -,21 display evidence of thermal metamorphism which can account for the disturbance in the K-Ar clock. However, some samples display neither shock nor thermal anealning effects to readily rationalize the difference between the K-Ar clock and more thermally resistant chronometers, (i.e. sample 60025,1 with Sm/Nd ages of ~4.44 Ga and ^{40}Ar/^{39}Ar ages of ~4.25 Ga; Table 1)).

Summary: 1) different rock types from Apollo 16, namely impact ejecta from the 230 m deep North Ray crater (soil 63503) offer insights into the impact history of the Moon, starting at least ~4.3 Ga ago; 2) lunar samples preserving pristine primary crystallization texture may "hide" a complex and likely later lengthy thermal metamorphism(s); 3) the complementary studies of shock features and ^{40}Ar/^{39}Ar age determination have the potential to better investigate the different Ar-loss and implantation environments; and 4) currently there is a need to better understand the distribution, volume, temperature, time interval and effects of the hot-ejecta on cold target rocks.

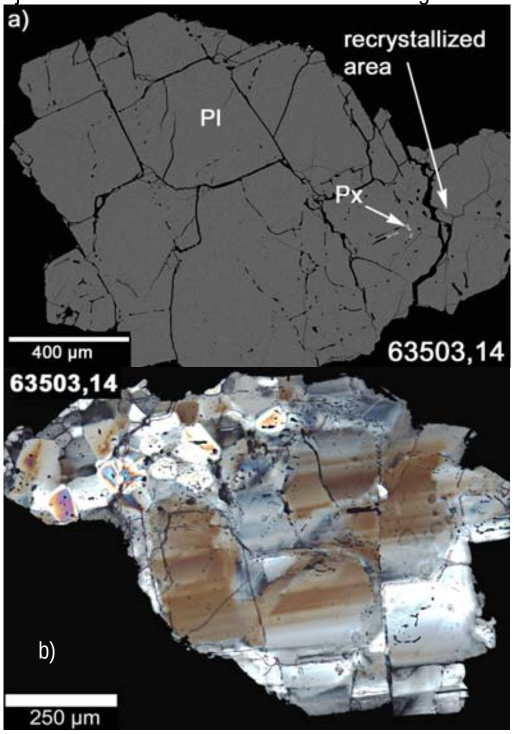


Figure 1: a) 63503,14 BSE image: anorthosite composed of single plagioclase grain and an attached zone of recrystallised plagioclase (lower right); b) transmitted light micrograph with crossed polarizers shows plagioclase with two texturally different regions: 120° grain boundaries (upper left) attached to a large & zoned single crystal

Acknowledgements: Use of online ADS-NASA and Lunar Compendium. Samples for this study were provided by Dr. Ben Weiss. Many thanks to Tony Irving for initial insights into the petrology of 63503 soil fragments.

References: [1] Tera et al. (1974) *EPSL,* 22, 1-21. [2] Turner and Cadogan (1975) Proc. 6thLPSC, 1509-1538. [3] Ryder (2002) *JGR 107*, 5022, 10.1029/2001JE001583. [4] Hartmann (1975) *Icarus 24, 181-187.* [5] Chapman et al. (2007) *Icarus* 189, 233-245. [6] Fernandes et al. (2008) Early S.S. Impact Bombardment, abst.#3028. [7] Fernandes et al. (submitted). [8] Carlson and Lugmair (1988) *EPSL,* 90, 119-130. [9] Nyquist et al. (1981) Proc. 12thLPSC,67-97. [10] Schaffer and Husain (1974) Proc. 5th LPSC 1541-1555. [11] Aeschilmann et al. (1982) 13thLPSC, 1-2 (abst.). [12] Maurer et al. (1978) *GCA* 74, 6636-6653. [13] Bikel (1977) Proc. 8th LPSC, 2007-2027. [14] Wilshire (1974) 5th LPSC (abst.), 846-847. [15] Jackson et al. (1975) *Geol. Soc. Am.* Bull. 86, 433-442. [16] James et al., (1991) Proc. 21st LPSC 63-87. [17] Deutsch and Stöffler (1987) GC*,* 51, 1951-1964. [18] Fernandes et al. (2009) *MaPS* 44, 805-821. [19] Fritz et al. (2011) this volume. [20] Fernandes et al. (2010) EPSC2010-237.