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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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. Furthermore, $^{40}\text{Ar}/^{39}\text{Ar}$ data obtained by the authors [6&7] are compared and compiled with literature data.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages summary: For samples 60025 and 78235, distinct crystallization and metamorphic ages were reported in the literature [8&9]. $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the thermally annealed anorthositic norite polymict breccia 78155 were reported by [10]. Our recent work [6&7], reported step heating $^{40}\text{Ar}/^{39}\text{Ar}$ ages, that are indistinguishable to those reported previously for these rocks [2&9-11]. The $^{40}\text{Ar}/^{39}\text{Ar}$ 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 and 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 crustal highland rocks 63503,16 and -21. The $^{40}\text{Ar}/^{39}\text{Ar}$ data for these three groups are presented in Table 1.
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 interstitial 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). 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 annealing 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.