LUNAR CATACLYSM OR LUNAR CATACLYSMS? A. A. Nemchin[1] and R. T. Pidgeon[1], [1]Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, Western Australia, 6845

Introduction: Presently accepted models of lunar evolution propose that the Moon has experienced an episode of intense meteoritic bombardment in the period between ~3.9 and 3.8 Myr. The timing of this episode, referred to as the late lunar cataclysm, is based on a large number of ages obtained using Rb-Sr, U-Pb, K-Ar and Ar-Ar systems on whole rock and mineral samples as well as impact melts from lunar highland rocks [1 and references therein]. However, the model of terminal lunar cataclysm has been questioned on the grounds that evidence of a pre 3.9 Ga impact history could have been obliterated by this late meteoritic bombardment [e.g. 2]. In this contribution our purpose is to discuss the problem of the lunar impact history in the light of new and previous SIMS U-Pb data on apatite and zircon from the same thin sections of breccias from Apollo 14 and Apollo 17 and SIMS U-Pb data of shocked and partially reconstituted zircon also from the breccia samples.

We have made SIMS U-Pb analyses of apatite and zircon from the same thin section from three breccia samples from Apollo 14 and one from Apollo 17. Both minerals are found within lithic clasts and in the breccia matrices. The size of the apatite and zircon grains found in the breccia matrices commonly far exceeds that of other minerals in the matrix suggesting that both apatite and zircon are mineral clasts that predate formation of the breccia samples.

The apatite U-Pb ages: The measured apatite $^{206}Pb/^{204}Pb$ ratios vary significantly between samples and correlate with the $^{206}Pb/^{204}Pb$ ratios of zircon grains analysed in the same thin sections. This indicates that most of the ^{204}Pb is related to contamination of the samples with terrestrial lead (most likely introduced during cutting and polishing of the thin sections). As the composition of initial Pb is uncertain, we have calculated ages using isochrones in $^{238}U/^{206}Pb$-$^{207}Pb/^{206}Pb$-$^{204}Pb/^{206}Pb$ space as this appears to involve the least number of assumptions. The resulting four ages are similar within the errors (3934±38 Ma for sample 14306,60; 3920±13Ma for sample 14066,47; 3894±78Ma for sample 14303,52 and 3928±20Ma for sample 73217,52). They are also similar to the age of 3909±8 Ma reported for the zircon grains from the crystallised impact melt observed in the lunar meteorite SAU169 [3]. Based on the high concentration of incompatible elements observed in this crystallised melt it was inferred to represent part of the Fra Mauro formation while the zircon age was interpreted to indicate the time of Imbrium impact.

Ages of cogenetic zircon and apatite: Both zircon and apatite in thin section 14306, 60 are found in a single norite clast. We interpret these as cogenetic and the zircon age of 4202±12, which is taken as the age of norite crystallization, is also interpreted as the primary age of the apatite. The present apatite age of 3934±38 Ma is significantly younger than the zircon age and is interpreted as having undergone complete Pb loss during the Imbrium event.

Zircon and apatite in the breccia matrices:

Apollo 14. Five zircon grains from the matrices of breccia thin section 14066,47 have ages of 4148±12 Ma (three grains), 4226±18 Ma and 4352±6 Ma. All three are significantly older than the apatite age of 3920±13 Ma, which we also interpret to have been completely reset during the Imbrium event. Sixteen analyses of eleven zircon grains from the sample 14303,52 show a spread of ages between 4343±10 and 4002±16 Ma. Even the youngest grain is still significantly older than the apatite age of 3894±78Ma. Importantly, three of the eleven grains are large enough to accommodate more than one analytical spot. One of these grains was analysed twice with both analyses giving similar ages defining an average of 4208±7 Ma. This suggests that this zircon has not been isotopically disturbed and that the age records the primary age of zircon crystallisation. The other two were analysed three times and show different degrees of variation in the ages of the different spots (4313±48 to 4129±40 Ma and 4343±10 to 4306±14 Ma). This suggests that these two grains were variably reset by a younger event.

Apollo 17. A similar pattern is shown by two zircon grains found in the section 73217, 52. Two analyses of one of these grains are indistinguishable within the error and define an average of 4332±5 Ma, while two analyses of the second grain give ages of 4308±44 Ma and 4241±12 Ma, which spread slightly outside the analytical errors, indicating the possibility of a minor disturbance of the U-Pb system. These are all older than the 3928±20Ma apatite age for sample 73217,52, which is identical to the apatite ages from the Apollo 14 samples, demonstrating a uniformity of behaviour of apatites in breccias from the Apollo 14 and 17 landing sites.

Disturbance of the U-Pb system in zircon: It is evident that while the apatite U-Pb system is completely reset during the 3.8-3.9 Ga meteorite flux, zircon grains largely preserve their primary ages. Only two zircon grains in the analysed population of 112 grains from Apollo 14 and 17 show ages of 3976±30 and 3969±6 Ma comparable although still slightly older than those of apatite. Nevertheless, about 10% of the grains that have been analysed more than once display significant variation of observed ages indicating some degree of disturbance. In most of these grains the small number of analytical spots (limited by 2 or 3) makes it difficult to determine if this disturbance represents a partial Pb loss during the 3.8-3.9 Ga event or complete resetting of U-Pb system as a result of some older impacts.

However we now have several examples where a large number of analyses on a single grain permit precise estimation of both primary and secondary ages.

One of these examples is a large zircon grain in the anorthosite clast found in the thin section 73235,82. Detailed imaging of this grain using electron microscope and RAMAN microprobe revealed that it consists of a combination of fragments that preserve primary ages and are surrounded by the secondary zircon that has lost crystallinity and experienced significant chemical changes [4]. This secondary zircon was interpreted as reflecting modifications induced by extreme shock. The consistent age of 4187±11 Ma obtained for this secondary zircon is therefore viewed as the time of impact that affected the anorthosite hosting this zircon grain.

Another example of an extensively studied grain is the large zircon fragment in the matrix of the sample 73215. Crystallographic orientation analysis using EBSD revealed a deformation pattern consistent with the shock. Several areas of this grain display chemical modifications similar to those observed in the secondary zircon in the sample 73235. U-Pb analyses of these areas define a consistent age of 4333±7 Ma, which is significantly younger than the ages observed in the less modified parts of the grain. This age is interpreted as reflecting the time of impact that disturbed lattice, chemistry and resetted U-Pb system in several domains within the zircon grain.

Reset apatite and zircon U-Pb ages and the lunar impact history: We interpret all apatite ages from the Apollo 14 and Apollo 17 samples as ages of complete resetting in response to the late 3.8-3.9 Ga meteorite flux referred to as the late cataclysm. However, the U-Pb systems in the bulk of zircon grains have not been disturbed by this major event. Several zircon grains show variation in their ages suggesting a disturbance of their U-Pb system. However, this disturbance is not necessary related to the late bombardment. Half of the zircons that show this disturbance have their youngest ages near 4.3 Ga, which could reflect an older impact event, possibly similar in age to that recorded in the grain from sample 73235. The youngest recorded ages of spots on the remaining grains (with the exception of one) are all older than 4.1 Ga. These results suggest a number of significant impacts occurred before the 3900 Ma cataclysm.

The observed difference in behaviour of apatite and zircon is consistent with the estimates of closure temperature of U-Pb system in these minerals. Experimental studies suggest that apatite will equilibrate its Pb at a temperatures above 450-500^{o}C, while the U-Pb system of zircon remains closed in excess of 1000 ^{o}C [5]. This suggests that while the late lunar cataclysm introduced enough energy to reset all apatite U-Pb systems within the Apollo 14 and Apollo 17 samples, it was incapable of producing a significant disturbance of the zircon grains. However, some zircon grains appear to be affected by pre 3.8-3.9 Ga impacts, suggesting extreme shock and temperature conditions occurred significantly before the ca 3.8-3.9 Ga cataclysm. Two early impacts at 4333±7 and 4187±11 Ma can be identified on the basis of our present data, which suggests that the impact history of the Moon extended far beyond the terminal lunar cataclysm.

References: [1] Stöffler D., Ryder G., Ivanov B.A., Artemieva N.A., Cintala M.J., and Grieve R.A.F., (2006). *Rev. Mineral. Geochem., 60,* 519-596. [2] Hartmann WK (2003). *Meteorit Planet Sci, 38,* 579-593. [3] Gnos E., Hofmann B. A., Al-Katgiri A., Lorenzetti S., Eugster O., Whitehouse M. J., Villa I. M. and Jull A. J. T., et al. (2004). *Science 305*, 657–659. [4] Pidgeon R. T., Nemchin A. A., van Bronswijk W., Geisler T., Meyer C., Compston W. and Williams I. (2007) *Geochim. Cosmochim. Acta 71*, 1370–1381. [5] Cherniak, D.J., Lanford, W.A., and Ryerson, F.J., (1991) *Geochim. Cosmochim. Acta, 55,* 1663-1673.