WHAT LUNAR ZIRCON AGES CAN TELL? M. L. Grange[1,2], A. A. Nemchin[1,2], R. T. Pidgeon[1,2], R. E Merle[1] and N. E. Timms[1], [1]Department of Applied Geology, Curtin University, GPO box 1987, Perth, WA 6845, Australia (m.grange@curtin.edu.au), [2]Centre for Lunar Science and Exploration.

Introduction: Zircon is an accessory mineral that crystallised from melt saturated in Zr, an incompatible trace element. On the Moon, Zr is found in quantity large enough to allow zircon to crystallise in rocks that are derived from the KREEP reservoir, which is left after the almost complete crystallisation of the lunar magma ocean and thus is enriched in incompatible elements such as K, REE, P, U and Th. In the Apollo sample collection, zircon is ubiquitous in impact melt breccias, either as a crystal fragments found in the matrix or as a cogenetic mineral included in its parent rocks which occur as small lithic clasts. Zircon has been used to reconstruct the magmatic history of the early Moon as well as its impact history, as some grains preserve impact features or have crystallised in impact melt. Over the least few years, a significant numbers of U-Pb ages on lunar zircons have been obtained for Apollo 12, 14, 15 and 17 landing sites [e.g., 1-3].

In this contribution, we describe the overall distribution of the published ages. We also discuss possible origins of the observed age groups in terms of magmatic and impact activity on the Moon.

Results: The combination of U-Pb ages obtained on zircon grains by [1-7] is shown in Figure 1.

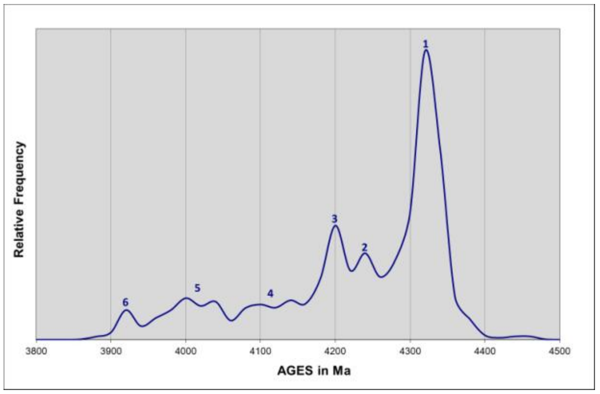

Figure 1: distribution of U-Pb ages of lunar zircon grains from Apollo 12, 14, 14 and 17 landing sites.

This plot considers a single age for every zircon grain, i.e. multiple analyses within single grains have been averaged. This plot has been constructed using a bin size of 20 Ma. Ages that are interpreted unambiguously in the original publication as impact ages, e.g. where a zircon has been shown to crystallise from an impact melt, are excluded; although there are very few such data [2-3-7].

The distribution of ages (Figure 1) indicates no formation of zircon before 4400 Ma or after 3900 Ma. It also shows several peaks: (1) the oldest is also the most prominent one and is centered around 4320 Ma, (2) the second one is close to 4240 Ma and is followed by (3) a peak at 4200 Ma. The younger peaks are less obvious and not as well defined as the first two: (4) and (5) are broad peaks separated by a small gap, they could arguably be split into narrower peaks, while the last peak of zircon ages is more clearly defined at 3920 Ma, although it is also the smallest.

Discussion: Results indicate a periodicity in the formation of zircon. Although zircon grains, as found in Apollo samples, were delivered to the surface by meteorite impact excavation of deep-seated rocks, the ages as shown above reflect ages of crystallization of zircon in their plutonic settings. Therefore, the observed periodicity of ages, although not regular, has to be explained in term of magmatic activity. In the following we discuss two mechanisms that can have triggered the formation of zircon.

Radioactive decay heat. The current model of lunar differentiation calls for the presence of the evolved reservoir KREEP. The crystallization of zircon in lunar rocks is linked to the presence of KREEP component in the magma. Therefore the study of ages of zircon that crystallised from such magma gives an insight into the activity related to the KREEP magmatic reservoir. The periodic activity of zircon formation may reflect periodic activity within the reservoir itself, where disturbance allows the formation of magma that can be emplaced into the lunar crust. Crystallisation of these magmas eventually formed the Mg-suite rocks , that contain zircon. As KREEP is the lunar reservoir enriched in the most imcompatible elements including K, U and Th, it can be assumed that disturbances in this reservoir are linked to accumulation of heat produced by the radioactive desintegration of these elements. Volumes of KREEP would accumulate enough heat along a certain period of time to induce melting. The magma created this way would provide a way to evacuate the heat to the crust, where it would crystallise and differentiate into a suite of rocks. The KREEP reservoir would also be cooler after the extraction of magma. After another period of radioactive disintegration, the reservoir would be hot enough to generate another pulse of magma, hence another period of zircon formation. Such mechanism would tend to weaken with time, as every magma generated carries heat as well as the radioactive elements themselves as they are all very incompatible and would be enriched in the melt, leaving a KREEP reservoir relatively depleted. Consequently, less heat would be produced through time, with smaller volumes of magma, generating less zircon as a result. This is illustrated by the younger and smaller peaks in the age distribution of Figure 1. In addition, closer to the time of formation of the Moon, the KREEP reservoir would have inherited some heat from the accretion and therefore be hotter. This is then likely to have more vigorous magmatic activity in the early times than later on.

Impact activity. Disturbances within the KREEP reservoir can also potentially be created by an external trigger such as shock waves expected to travel through the lunar interior as a result of a massive impacts hitting the surface. For example, Imbrium basin is about 1200 km in diameter and may have created a transient crater of several hundreds of km according to [8]. The formation of such large structure would have doubtlessly affect the deeper part of the Moon.

Consequently another possibility to form zircon would be to create impact melt sheets large enough so that they could differentiate, producing enrichement in incompatible elements and then allow the crystallisation of zircon. This mechanism is observed on Earth for large impact structures such as the Sudbury and Manicouagan craters. However, it has been never evoked for the Moon, perhaps because it was already a controversial subject for terrestrial structures. One would actually expect massive heat disturbance of the lunar crust and potentially mantle when the Moon is hit by meteorites responsible for the formation of basin size craters. Such impact could have created enough melt to produce large sheets that could cool down slowly and differentiate as would magma generated by an internal heat production. The terrestrial craters mentionned above are at least one order of magnitude smaller than the lunar basins, and still have differentiated impact melt sheets. Therefore, it is very likely that massive craters of the Moon are accompanied by large volume of melt, able to differentiate as crustal plutons would do, and produce residual melts evolved enough to crystallise zircon. In such scenario, the periodicity in zircon ages as shown in Figure 1 would reflect the formation of these melt sheets, or at least the last stages of the diffentiation of these sheets. They would consequently reflect the collisions of massive meteorites with the early Moon.

If this is true, the curve as shown in Figure 1 reflects the meteorite impact flux that affected the early Moon: it lasted from about 4350 to 3900 Ma, with a drecrease in either size or frequency of impacts along this time interval. No major impact able to produce melt sheet took place after 3900 Ma.

References: [1] Nemchin A. A. et al. (2008) *GCA, 72*, 668–689. [2] Grange M. L. et al. (2009) *GCA, 73*, 3093–3107. [3] Liu et al. (2012) *EPSL, 319-320*, 277–286. [4] Grange M. L. et al. (2011), *GCA*, *75*, 2213–2232. [4] Taylor D. J. et al. (2009), *EPSL*, *279*, 157–164. [5] Grange M. L. et al. (2013), *GCA*, *101*, 112–132. [6] Merle R. E. et al., (in prep, Apollo 14). [7] Grange M. L. et al. (in prep, Apollo 15). [8] French B. M. (1998) *LPI Contribution No. 954*, 120 pp.