EVIDENCE FOR A LUNAR "CATACLYSM" AT 4.34 GA FROM ZIRCON U-Pb SYSTEMS.

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It is well accepted that the cratering rate on the Moon has decreased over time but opinions vary widely on the behaviour of the impacting rate. The problem is that the flux of impactors has saturated the present surface with craters obliterating the early cratering record and pulverising early rocks into microbreccias, making it extremely difficult to trace the cratering record back in time. The impactors themselves cover a range of sizes from dust size to massive bolides capable of forming craters 100's of kilometers across. The effects of these events are aptly summarized by the question of Hartman [1] " As we go back in time is there a point where we lose datable rock units because they have been destroyed by being saturated with large craters?" In terms of the geochronological interrogation of lunar rocks the question not only refers to the destruction of datable rocks but also to the thermal effects on the stability of radiometric systems in rocks that have survived. This is well illustrated by the response of the K-Ar and Rb-Sr systems on minerals and whole rocks and U-Pb systems on whole rocks and phosphates to the giant Imbrium impact.

The consistency of total rock U-Pb K-Ar [2] and Rb-Sr isochron ages of sample of highland breccias at 3.8-3.9 Ga led Tera et al. [3] to propose that the Moon had experienced an event or series of events in a narrow time interval at ~3.9 Ga. They referred to this as the lunar cataclysm and associated this with the Imbrium impact and very possibly the formation of Crisium and Orientale and other major basins in a narrow time interval of ~2x 10^8yr or less. Following this paper numerous studies on lunar materials, using Rb-Sr and Ar-Ar techniques , have confirmed the concept of a lunar cataclysm at ~3.9 Ga [4]. Most recently our SHRIMP U-Pb analyses on apatite from Apollo 14 and Apollo 17 impact breccias have shown that this mineral has been isotopically reset at ~3.9 Ga, thus providing further evidence for a profound heating event on the Moon at ~3.9Ga [4]. Evidence for a major ~3.9 Ga event is also found in lunar meteorites. For example Gnos et al. [5] reported a SIMS U-Pb age of 3909±13 Ma for zircon from the Sayh al Uhaymir 169 lunar meteorite.

In constrast with these age results, almost all of the considerable number of zircon grains in lunar breccias isotopically analysed by SIMS have U-Pb ages older than 3.9 Ga [6,7]. Zircon, therefore, records earlier events than the Imbrium impact. However, about 10% of lunar zircons analysed more than once display a significant difference in the measured ages indicating that grains have experienced a degree of isotopic disturbance. In most of these grains the small number of analytical spots makes it difficult to determine whether the disturbance represents a partial Pb loss during the 3.8-3.9 Ga event or resetting of the U-Pb system as a result of some older impact. To resolve such questions we have made comprehensive SIMS analyses of selected grains and combined these data with other evidence including cathodoluminescence (CL) imagery of zircon internal structures, zircon morphology, zircon chemistry and textural relations between zircon and other minerals in the fragment of host rock in the breccia. An example is the zircon aggregate in an anorthosite fragment from thin section 73235,82, known as the pomegranate zircon [8]. Besides detailed SIMS U-Pb analyses, CL imagery, polarizing microscopy, RAMAN spectroscopy and U-Th chemistry were applied to reveal that the aggregate was made up of numerous broken and displaced fragments of an original zircon grain that retained the original age and chemistry of formation, set in a matrix of zircon that had reduced crystallinity, altered U-Th chemistry and had lost all radiogenic Pb. The interpretation of the age of 4,187±11 Ma for this altered zircon as the time of impact illustrates very well the importance of zircon in dating lunar impact events.

The zircon U-Pb system therefore provides one, and possibly the only, means of detecting and dating large pre-Imbrium impacts. Textural relationships between zircon and surrounding minerals and shock effects on individual grains provide the key to interpeting the signficance of the SIMS data. Extreme temperature/shock conditions can melt the target rocks and produce new magmas that on crystallizing can generate zircons with a record of the age of impact. The thermal shock can also produce partial melting of more remote KREEP bearing rocks which on cooling could also produce zircon. In addition, extreme shock and high temperatures could disturb the U-Pb systems of existing zircons in surviving host rocks, as in the example of the pomegranate aggregate, leaving a record of the age of the primary zircon and the age of impact. The application of zircon U-Pb systems in lunar geochronology is therefore the opposite to that posed by the question of Hartman which refers to most geochronometric systems, in that as we go back in time zircon will register those impacts large enough to produce zircon-crystallizing magmas or melts and large enough to remove radiogenic Pb from existing zircon.

The size of the impact event would most likely be indicated by the size of the age peak in the overall distribution of lunar zircon ages.

In the following we apply these concepts to examine evidence from published zircon geochronological studies for a massive impact on the Moon at ~4.34 Ga. The first evidence for this major impact comes from the zircon U-Pb age of 4335±5 Ma for acicular zircon grown in impact melt from breccia 73217 [9]. These thin, delicate crystals would not have survived if they existed prior to impact. A second type of rounded anhedral zircon in thin section 73217,52 occurs in a granoblastic rock fragment containing pyroxene, merrillite, apatite and glass [9]. The U-Pb age of this zircon of 7332±7Ma, is interpreted as dating high temperature crystallization of a possibly shock generated magma. Wheras these results provide information on the ages of impact produced melt other evidence exists in the form of a profound shock disturbance of the U-Pb system of an older zircon. The discovery of a 4417±6 Ma zircon in thin section 72215,195 provided a precise younger limit for the solidification of the lunar magma ocean [10]. However, this zircon has a very inhomogeneous age pattern indicating that it has been severely disturbed by impact shock and an accompanying thermal spike. The pattern of ages shows that this grain has experienced a variable loss of radiogenic Pb, from complete Pb loss and partial loss of U and Th in some parts, to areas of the grain that have remained a closed system and retained all original radiogenic Pb. SIMS ages of those parts of the grain that have lost all radiogenic Pb are consistent at 4334±10 Ma, and are interpreted as dating the impact event. The coincidence of this age with the zircon age of ~4334 Ma for crystallization of impact generated melt is interpreted as evidence for a severe lunar impact at this time. Some idea of the regional significance of this event can be obtained from the $^{207}Pb/^{206}Pb$ age distributions of all dated zircons from lunar breccias from Apollo 14 and 17 [7]. The strongest peaks in the age distributions of both zircon populations, determined at the modal values, are at ~4338Ma (Apollo 14) and ~4341Ma (Apollo 17). These age peaks are remarkably similar to the ages of melt zircon and the age of impact disturbance of the oldest zircon grain. Whereas further SIMS and chemical study of complex zircon grains and SIMS and textural study of zircons from impact melts will reveal the ages of other lunar impacts the dominant age peak at ~ 4.34 Ga in zircon populations from Apollo 14 and 17, suggests that the impact at this time was possibly the largest in lunar history since the crystallization of the magma ocean

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