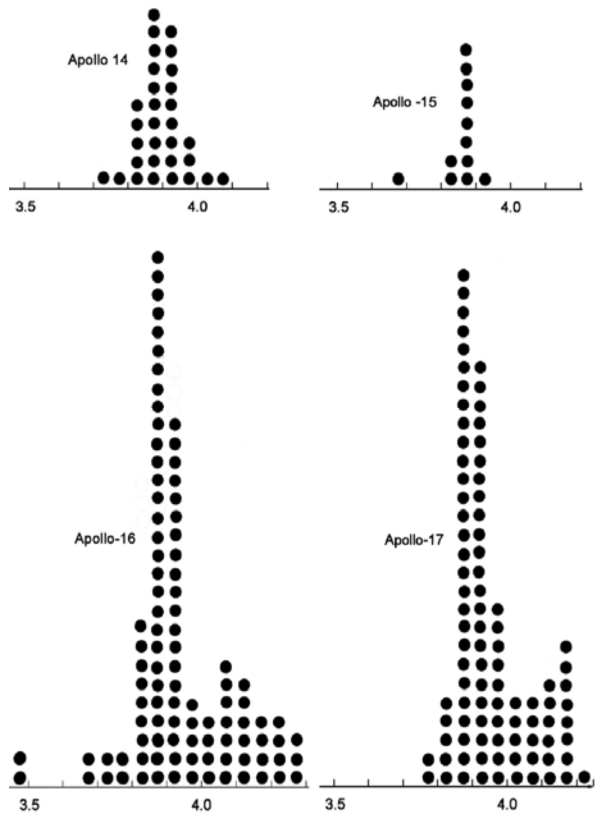
ON THE HISTORY OF EARLY METEORITIC BOMBARDMENT OF THE MOON: DID THE LUNAR TERMINAL CATACLYSM OCCUR? Gerhard Neukum[1] Alexander Basilevsky[1,2], Thomas Kneissl[1], Greg Michael[1], Boris Ivanov[1,3] 1-Free University of Berlin, Berlin, Germany; 2 - Vernadsky Institute, Moscow, Russia; 3 – Institute of Dynamics of Geospheres, Moscow.

Introduction: Here we consider the issue of the terminal lunar cataclysm (also called Late Heavy Bombardment) which is a potential feature of the so-called early intense bombardment. The concept of the latter in relation to the Moon was first suggested even before the Apollo-Luna sample returns (Hartmann, 1965, 1966). The isotopic measurements of absolute ages of samples of lunar rocks brought by the Apollo/Luna missions seemed to confirm this concept (e.g., Papanastassiou and Wasserburg, 1972; Hartmann, 1972; Turner et al., 1973; Turner, 1977). Some of the works considered the early intense bombardment as the final stages of the planetary accretion with the half-life of the bombardment rate decrease being $\leq 10^8$ years (e.g., Hartmann, 1972; Neukum et al., 1975), while others considered it the result of large collisions in the asteroid belt (e.g., Turner et al., 1973).

The hypothesis of a "lunar terminal cataclysm" is one possible scenario of the early intense bombardment. It suggests that approximately 3.9 Ga ago there was a strong peak in meteorite bombardment of the Moon when most of the craters observed in the lunar highlands and thus most of the lunar highland impact breccias were formed (Tera et al., 1973, 1974). It is based on the observation that the ages of highland samples from all lunar missions determined by a variety of isotopic techniques group around 3.9–4.0 Ga. This is considered as evidence for widespread shock metamorphism and element redistribution resulting from large-scale impacts on the Moon during that relatively narrow time interval. Since its first publication, the hypothesis has been widely debated with arguments for and against (e.g., Hartmann, 1975; Grinspoon, 1989; Cohen et al., 2000; Stoffler, Ryder, 2001; Hartmann, 2003; Chapman et al., 2007; Hartmann et al., 2007). In this paper we reconsider whether the lunar terminal cataclysm did occur. For this purpose we first analyze the published results of K-Ar dating of lunar highland rocks (mostly breccias, impact melt and no-melt breccias).

Summary of Ar-Ar dating of lunar highland rocks: Here we consider the results of K-Ar dating of samples of lunar highland rocks, which are mostly made by application of the Ar-Ar technique. The K-Ar clock is easily reset by thermal events so the K-Ar dating is most sensitive to shock metamorphism and impact melting resulting from meteoritic bombardment. The major source of information for the samples considered and their ages is *The Lunar Sample Compendium* compiled by Charles Meyer at the JSC NASA (http://curator.jsc.nasa.gov/ lunar/compendium.cfm) with additions from recent publications. Below are plots of Ar-Ar ages of highland rocks brought by the Apollo 14, 15, 16 and 17 missions. The Apollo 14 and 15 missions brought samples from the sites located within the ejecta blankets of the Imbrium basin and thus dating when this basin formed (peaks at ~3.9 Ga). The Apollo 16 and 17 missions brought samples from sites where, together with distant ejecta from the Imbrium basin, ejecta from the nearby Nectaris and Serenitatis basins are expected.



The above histograms for the Apollo 14 and 15 rocks show a prominent peak at ~3.9 Ga (which we interpret as the Imbrium signature) while histograms for the Apollo 16 and 17 rocks show not only the prominent peak at ~3.9 Ga, but secondary peaks at ~4.1 and 4.2 Ga.

This, in our opinion, suggests that the Nectaris and Serenitatis basins formed 100-200 My before Imbrium (~3.9 Ga), which is in contradiction with the hypothesis of a lunar cataclysm.

Summary of Ar-Ar dating of lunar meteorites: In an attempt to minimize the influence of Imbrium basin ejecta we summarized data on Ar-Ar ages of lunar meteorites, which are believed to be delivered to Earth from randomly distributed sites on the lunar globe. The sources of this information are *The Lunar Meteorite Compendium* compiled by Kevin Righter, also at the NASA Johnson Space Center, Houston, http://curator.jsc.nasa.gov/antmet/lmc/index.cfm. and the *Compendium of Lunar Meteorites*, run by Randy Korotev, Washington University in St. Louis, http://curator.jsc.nasa.gov/antmet/lmc/index.cfm. Data on the ages of lunar meteorites from recent publications are also included. Based on these sources we have compiled results of Ar-Ar dating of 91 clasts from 20 lunar meteorites. A summary of Ar-Ar ages of highland rocks from lunar meteorites is shown in the form of a histogram at the end of this abstract.

It is seen in this histogram that the Ar-Ar ages of lunar meteorites, contrary to the Apollo highland rocks, show no prominent peak at 3.9 Ga. Instead there is a rather uniform frequency distribution of age values within the 2.4 to 4.25 Ga age interval, while within the 1.5 to 2.4 Ga age interval the frequency is also close to uniform, but there it is obviously lower. This character of distribution of ages of highland rocks and of lunar meteorites was noticed and discussed by Hartmann (2003), Hartmann et al. (2007) and Chapman et al. (2007). Folowing these authors we believe that this age distribution questions the hypothesis of a lunar cataclysm.

Summary of the cratering record of pre-mare impact structures: Using crater size-frequency data in combination with superpositional relationships it is possible to set up a complete relative stratigraphy for all established lunar pre-mare basins with diameters larger than 300 km. For this purpose we used mainly three different datasets: (a) crater size-frequency data as published by Wilhelms (1987) and Neukum (1977, 1983), (b) stratigraphic relationships as determined by Wilhelms (1987) (this contains superpositional relations and so-called “age groups”), and (c) newly determined crater-size frequency data for the South Pole-Aitken basin. The resulting relative stratigraphy indicates that 13 basins are younger than Nectaris and 32 basins are older. Assuming a formation age of 4.1Ga for Nectaris, this is in contradiction with a LHB spike in the lunar cratering rate and the according hypothesis of a lunar cataclysm.

Megaregolith evolution modelling: We have constructed a model to consider the production of impact melt on the Moon, together with its redistribution, burial and mixing at the lunar surface by impact 'gardening'. We expect to obtain an insight into the relative frequency of melts of different ages at the near-surface — the source of both the lunar samples and meteorites — for various hypothesised scenarios of the impact rate history. A terminal lunar cataclysm, if it occurred, should have left a global signature in the melts present at the surface, which would be identifiable in a sufficiently large sampling from random sites, as given by the lunar meteorites. The model will allow us to constrain the impact rate history to those scenarios consistent with the present sampling.

Conclusions: It follows from the above considerations that the hypothesis of a terminal lunar cataclysm is not consistent with the lunar meteorite record, and likely did not occur. The peak at ~3.9 Ga seen in the Apollo samples is interpreted as the signature of the Imbrium basin. A final solution to this problem needs new sample return missions from the Moon. Samples dating the largest and probably the most ancient South pole-Aitken basin would be especially helpful.

References:

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