WHAT IS THE AGE OF THE NECTARIS BASIN? NEW Re-Os CONSTRAINTS FOR A PRE-4.0 Ga BOMBARDMENT HISTORY OF THE MOON

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Introduction: The surface of the Moon is characterized by large impact basins, most of which are believed to have formed during a brief period of intense bombardment of the inner solar system [1]. The chronology of large lunar impact basins provides critical information on the Hadean impact flux rate to the Moon, and by inference to the Earth and other terrestrial planets. The majority of ages obtained on lunar impact melt rocks fall within a restricted range from 3.8 to 4.0 Ga. These data and the apparent scarcity of ages older than 4.0 Ga, support the argument for a pronounced spike in the flux of large impacting bodies in the inner solar system around 3.9 Ga, the terminal lunar cataclysm or Late Heavy Bombardment [1-3]. In contrast, some studies interpret cratering record and age data to be consistent with a steady decline of impact rates with time and argue that the records of earlier impacts were erased by megaregolith evlution and burial bias [4-7].

The age of the Nectaris basin is of particular interest in order to constrain the timing of the mass flux rate to the Moon. The sharpness of the spike in the lunar mass flux curve was largely anchored by the age of Nectaris [1] (Fig. 2). The preferred age of Nectaris based on Ar-Ar age data is 3.90-3.92 Ga [1,3,8], but an age of 4.1-4.2 Ga has also been discussed [9-11] and recent data on Apollo 16 samples suggest that the exact age of the basin remains poorly constrained [12,13].

Here, we report the first precise Re-Os isochron age on a lunar impact melt rock. We discuss the radiometric age in the light of the landing site stratigraphy, compositional information on Apollo 16 samples, and proximity to the Nectaris basin.

Sample Material and Analytical Techniques: Apollo 16 sample 67935 has a fine-grained subophitic basalt texture and is characterized by relatively abundant Fe metal-troilite intergrowths.

Two pieces of Apollo 16 sample 67935 weighting 1.14 g in total were crushed into small chips using an alumina ceramic mortar. From these chips about 10 subsample aliquots weighting ~100 mg were weighted into quartz glass digestion vessels. A Mixed ^{185}Re-^{190}Os spike solution was added, followed by 1 ml conc. HCl and 2 ml conc. HNO_3. Samples and blanks were digested in a high-pressure asher for 16 h at 320°C. A detailed description of the chemical separation procedures for Re and Os is provided in [15].

Concentrations of Re and Os were determined by isotope dilution, ICP-MS (Re) and N-TIMS (Os) analysis. Osmium isotopic compositions were measured by N-TIMS on a Triton at the FU Berlin. Signals were detected on Faraday cups in static mode or on a secondary electron multiplier (SEM) operating in pulse counting mode. Measured ratios were corrected for isobaric OsO_3^- interferences. Mass fractionation was corrected using a linear law and ^{192}Os/^{188}Os = 3.08271. Values and long-term reproducibility for ^{187}Os/^{188}Os of the UMD Os standard solution were 0.11380 ± 0.00003 (2s, n = 43) on Faraday cups and 0.1141 ± 0.0003 (2s, n = 19) for SEM measurements. Total analytical blanks during the work on lunar samples had an average ^{187}Os/^{188}Os of 0.210±0.055, and 1.1±0.9 pg Os and 7±2 pg Re (1sd, n=14). Average blank contributions for Apollo samples were <0.14% for Os and between 1.9–8.5% for Re. All concentrations and isotopic data were corrected for blank contributions. The precision of the HSE concentration data estimated based on blank contribution and variation in the blank is conservatively estimated to be better than 0.12% for Os and 2.5% for Re. Accuracy and reproducibility of the analytical technique can be assessed from the results obtained for the Smithsonian Allende and the UB-N ultramafic reference powders [15,16] in comparison to results obtained in other laboratories.

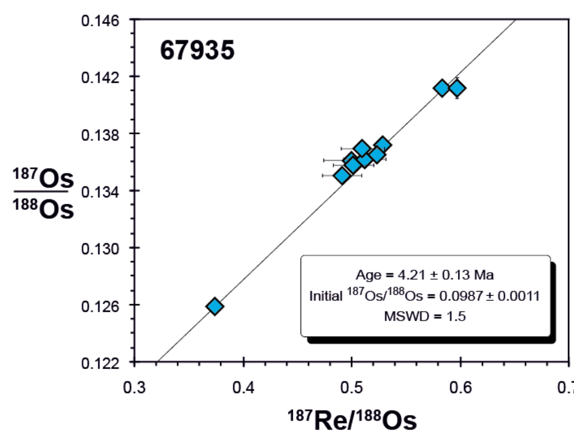

Fig. 1. Isochron diagram for subsamples of Apollo 16 sample 67935. Uncertainties (2σ) for ^{187}Os/^{188}Os and ^{187}Re/^{188}Os include uncertainties in blank correction.

Results and Discussion: Re-Os isotope data for subsample aliquots of 67935 yield an internal isochron, calculated using ISOPLOT [17], corresponding to an age of 4.21 ± 0.13 Ga and initial ^{187}Os/^{188}Os of 0.0987 ± 0.0011 (MSWD = 1.5) (Fig. 1). In a plot of 1/Os vs. ^{187}Os/^{188}Os no systematic relationship between Os isotopic composition and Os concentration exists, thus eliminating mixing processes as a cause for the variation. The Re-Os isochron age for 67935 most probably represents the age of the impact that produced the impact melt rock. Relatively high abundances of Re and Os in ancient lunar impact melt rocks reflect addition of these elements by meteoritic impactors. Some Apollo 16 samples, including 67935, have been known for their unusually fractionated HSE ratios [18,19]. Fractionated Re/Os in subsamples of 67935 can be explained by centimetre-scale partitioning between solid metal and C- and S-bearing metallic liquids during cooling of the impact melt sheets, as indicated by FeNi metal and troilite intergrowths in 67935.

The Re-Os age of 67935 is significantly older than Ar-Ar ages obtained for the majority of Apollo 16 samples, which typically range from 3.75 – 3.96 Ga [13,20]. For Apollo 16 granulitic impactite 67955 a Sm-Nd age of 4.20 ± 0.07 Ga was reported [20]. The poikilitic rock texture of 67955 was interpreted to have formed by impact melting and recrystallization [21,22]. The exact relationship of the granulites with the Nectaris basin remains unclear, however, 67955 was collected from the same boulder as 67935 on the rim of the North Ray Crater at the Apollo 16 landing site. The boulder most probably represents a part of the Descartes formation, which has been interpreted to derive from the Nectaris impact [3,14]. Some samples from the Descartes Formation show younger Ar-ages, consistent with an Imbrium provenance, but 4.0-4.2 Ga ages have been reported as well [12,13]. These ages may indicate a heterogeneous provenance of the Descartes Formation, or, may reflect resetting of Ar ages by younger impact events. A selection of high quality Ar-Ar data shows the existence of two age clusters near 3.9 Ga and 4.1 Ga for Apollo 16 impact melt rocks [12].

The new age data for 67935 and 67955, and their different HSE composition show that there was a significant pre-4.0 Ga bombardment history affecting the highlands near Nectaris. Both, the Re-Os age of 4.21 ± 0.13 Ga obtained for 67935 (Fig. 1) and the 4.20 ± 0.07 Ga metamorphic recrystallization age of 67955 obtained by the Sm-Nd method [21] seem to be unaffected by later basin-forming impacts, likely because resetting these chronometers would require either melting or high-grade metamorphic conditions. These new age data supports previous notions that the Nectaris impact basin may be as old as 4.2 Ga [9-11,24,25]. An age of 4.2 Ga for Nectaris would significantly affect the lunar mass accretion rate and weaken the hypothesis of a Late Heavy Bombardment at around 3.9 Ga (Fi. 2). Assuming a 4.21 Ga age for Nectaris, the resulting average accretion flux between 4.21-3.82 Ga would be ~5×10^{12} g/year, about an order of magnitude lower compared to the ~2×10^{13} g/year estimated if Nectaris has formed 3.92 Ga [1].

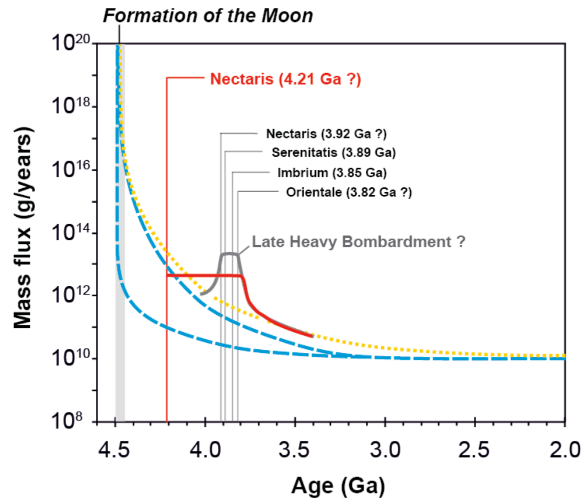

Fig. 2. Accretionary mass flux *vs.* time after [1]. Dashed blue and yellow lines correspond to present day background fluxes extrapolated back in time to the early solar system, elevated flux (yellow) according to [23]. Preferred ages for large impact basins are indicated by grey vertical lines and represent the basis for arguments for a pronounced spike in flux of large impacting bodies (solid grey curve). The solid red line corresponds to the average mass flux assuming a 4.21 age for the Nectaris basin.

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