CHRONOLOGY AND PROVENANCE OF LUNAR KREEP: A 4.0 OR 4.1 Ga AGE FOR SERENITATIS?

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Introduction: Stöffler and Ryder [1] summarized the radiometric ages of lunar samples and lunar surface crater frequencies to derive a chronological standard for the inner solar system. They concluded that the sampled basins formed within the narrow time interval from 3.92±0.03 Ga ago (Nectaris) to 3.85±0.02 Ga ago (Imbrium). We examine the question of basin ages using Rb-Sr isotopic data. Rb-Sr isochrons provide initial $^{87}Sr/^{86}Sr$ values (I_{Sr}) as well as ages (T). I_{Sr} is a tracer for lunar KREEP, which often appears to be associated with lunar basins. A variety of KREEP (or urKREEP) is widely assumed to form a lower crustal layer on the moon. (See [2], Fig. 1, for example.) From these considerations we suggest that the Serentitatis basin may be as old as ~4.1 Ga.

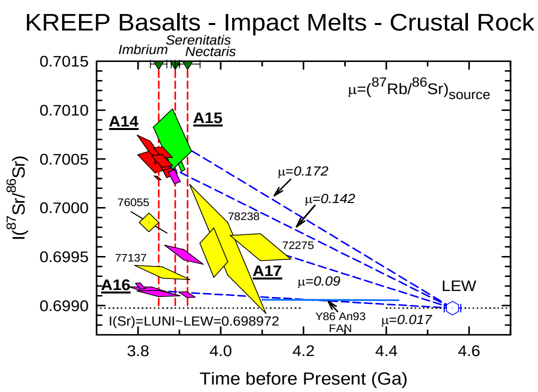

Figure 1. (T,I_{Sr}) values for KREEP basalts and KREEP-enriched impact melts compared to values for crustal rocks. Data from the literature except 78238 norite [9].

(T,I_{Sr}) for KREEP basalts and melt rocks: Fig. 1 summarizes (T,I_{Sr}) values for KREEP basalts and KREEP-rich melt-rocks from Rb-Sr mineral isochrons. A mineral isochron requires the initial existence of a magma which cools slowly enough to allow minerals to nucleate and grow, a requirement satisfied by most indogenously generated basalts, so many of the data plotted in Fig. 1 are for A14 and A15 KREEP basalts and A17 KREEPy basalts. Interpreted in the customary manner, the relatively high I_{Sr} values for these basalts imply that they were produced by partial melting of a portion of the lunar mantle having high source region $(^{87}Rb/^{86}Sr)_{source}$ (μ) values ranging from μ ~ 0.09 for A17 KREEPy basalts to ~0.17 for A15 KREEP basalts.

Distribution of Rb-Sr Ages: Fig. 2 shows a comined probability distribution for the ages shown in Fig. 1. The figure is constructed by expressing the

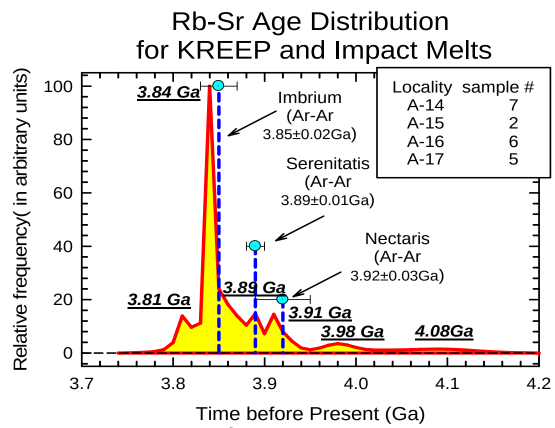

Figure 2. Rb-Sr ages of KREEP basalts and highland melt-rocks.

measured age and error limits as a gaussian distribution in time. Data for several impact-melt rocks are included, including all of the A16 rocks for which (T,I_{Sr}) data are shown in Fig. 1. The oldest Rb-Sr ages of the A16 rocks are in agreement with a 3.92±0.03 Ga age given for the Nectaris basin [1]. Some of the A16 impact melt rocks are younger, consistent with formation via local, smaller-scale, cratering. Alternatively, their ages also are consistent with the 3.85±0.02 Ga age given for the Imbrium event by [1]. This suggests that they may have been ballistically transported to the A16 site by the Imbrium event, but they lack the characteristically high I_{Sr} values of Imbrium ejecta as found at the A14 Fra Mauro site, for example. For that reason, we consider it unlikely that they are Imbriuim ejecta.

^{39}Ar-^{40}Ar ages for A16 melt rocks from [3] also are shown in Fig. 3 in comparison to Rb-Sr ages from the literature [4,5] recalculated with decay constant λ_{87} =

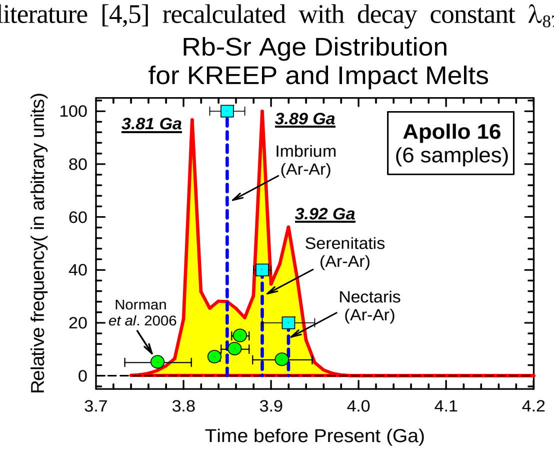

Figure 3. Combined probability distribution for A16 Rb-Sr ages.

0.01402 Ga^{-1}. There is good agreement, even to the existence of four dated events. This observation and close agreement between the Rb-Sr and ^{39}Ar-^{40}Ar ages for Imbrium (Fig.2) demonstrate general concordancy between ages obtained by the two methods.

Fig. 4 shows lack of agreement between the Rb-Sr ages of A17 rocks and the suggested ages of the Serenitatis and Nectaris basins, however. As for the A16 data, the youngest ages are approximately consistent with the ~3.85 Ga age of the Imbrium basin. However the corresponding rocks have lower initial $^{87}Sr/^{86}Sr$ than characteristic of KREEP-rich ejecta from Imbrium. We think it more likely that, like the A16 melt rocks, they represent local cratering events. There is no correspondence between the 3.89±0.01 Ga age suggested for Serentitatis by [1] and any preferred age shown by the Rb-Sr data. In principle, this could be a selection effect caused by the inability to date relevant impact melt samples by Rb-Sr mineral isochron techniques. However, this does not appear to have been a factor for rocks from the other landing sites. A14 and A15 KREEP basalts, for example, appear to record the Imbrium event, perhaps via impact-triggered volcanism. The analogous indogenously generated KREEPy basalts at the A17 site are ~4.1 Ga old. They predate the Serenitatis event if the latter occurred at ~3.89 Ga.

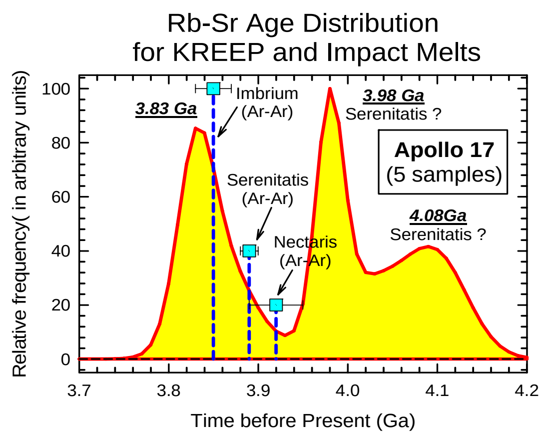

Figure 4. Combined probability distribution for A17 Rb-Sr ages.

Sr isotopic data for KREEP-rich breccias: Fig. 5 may contain some additional clues to interpreting the A17 data. It shows "initial" $^{87}Sr/^{86}Sr$ values calculated from bulk analyses of the matrices of breccias [6,7] that can be reasonably traced to formation of the Imbrium (A14, A15) and Serenitatis basins (A17). These breccia matrices contain multiple components, but their Sr-isotopic compositions are clearly dominated by the KREEP component(s). These data have the geological advantage that the A17 breccia matrices come from boulders that can be traced to the South and North Massifs of the Taurus mountains. Compared to known

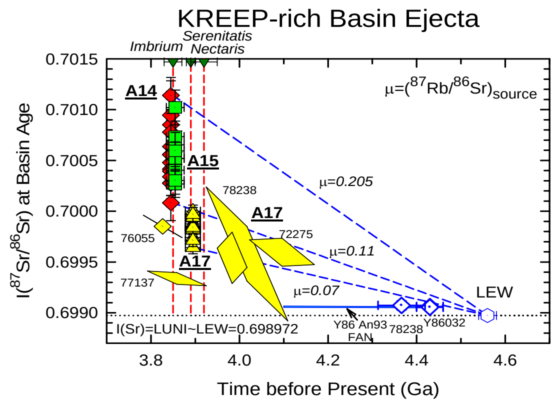

Figure 5. I_{Sr} for KREEP-rich basin ejecta at the basin age.

Imbrium ejecta, they had distinctively lower $^{87}Sr/^{86}Sr$ ratios at ~3.89 Ga ago. Like the impact-melt sample 76055, their $^{87}Sr/^{86}Sr$ ratios are consistent with radiogenic growth in the same "source" with μ ~ 0.09 as for the A17 KREEPy basalt clast in breccia 72275.

Conclusions: By analogy to the apparent linkage via impact-triggered volcanism or impact melting between the ages of A14 and A15 KREEP basalts and the age of the Imbrium basin, there is a significant probability that the Serenitatis basin is as old as ~4.1 Ga. Alternatively, ~4.1 Ga A17 KREEPy basalts may have formed the protolith into which the Serenitatis impact occurred. In this case, the Rb-Sr data suggest a probable age of ~3.98 Ga for the Serentitatis event. The latter age is a particularly good fit to the cratering chronology of [8] (Fig. 6).

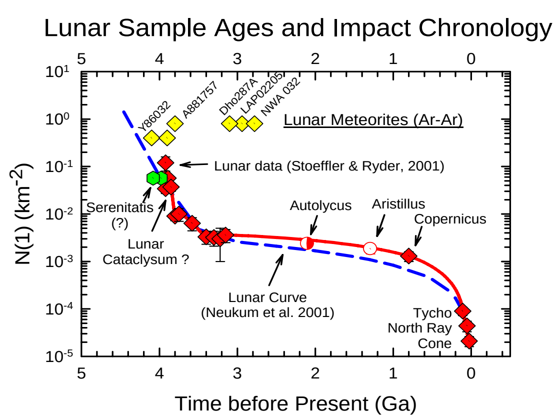

Figure 6. Possible Serenitatis ages compared to the cratering chronologies of Neukum et al. [8] and Stöffler et al. [1].

References: [1] Stöffler D. and Ryder G. (2001) *Space Sci. Rev., 96,* 9-54. [2] Ryder G. and Wood J. (1977) *PLSC8,* 655-668. [3] Norman M. D. et al. (2006) *GCA 70,* 6032-6049. [4] Reimold W.U. et al. (1985) *PLPSC-15th, JGR, 90,* C431-C448. [5] Deutsch A. (1986) *LPS XVII,* 176-177 [6] Nyquist L. E. et al. (1974) *PLSC5* 1515-1539.[7] Nyquist L.E. et al. (1975) PLPSC-6th, 1445-1465. [8] Neukum G. et al. (2001) *Space Sci. Rev., 96,* 55-86. [9] Edmunson J. (2007) Ph. D. thesis.