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Biases in lunar impactite chronometry

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Grenville Turner's pioneering Ar-Ar work on lunar highland rocks has shaped debates on the ages of lunar basins and the early lunar bombardment history. Although interpretations of some of the data were challenging, the predominance of ages near 3.9 Ga and more scarce older dates were major results that were confirmed by many other studies. Over the last two decades, *in situ* U-Pb dating methods have been applied more often. An advantage of *in situ* methods is that they can utilize textural, mineralogical and microchemical information to understand the formation and modification of the chronometer minerals and their local environment.

A few examples illustrate the response of different chronometers, in impactites with different thermal histories. For instance, in the lunar granulite 78155, zircon and Ca-phosphates yield similar Pb-Pb dates of 4.2-4.3 Ga (this work), which partially overlap earlier Ar-Ar dates and conventional Pb-Pb isochron dates (between 4.1 and 4.2 Ga). The consistently old ages reflect effective thermal annealing of preexisting breccia by hot ejecta, presumably from a basin-forming impact, and little influence by later heating events. In contrast, breccias like 15455 and 67955 show textural evidence for a multi-stage heating history and display bi- or multimodal distributions of dates. Zirconium minerals in these breccias yield old ages and relatively homogeneous distributions at 4.2 (in 15455 and 67955) and 4.33 Ga (in 15455). In contrast, Ca-phosphate dates tend to cluster near 3.92 Ga (15455), or spread on the concordia between 3.9 Ga and older dates, due to variable discordance (67955). Published Ar-Ar data on 15455 show disturbed systematics by heating events that occurred at or after 3.9 Ga. Thus, these and data on other samples show clear biases of chronometer systems in complex breccias, with Ca-phosphates and Ar-Ar data preferably recording younger heating events, whereas zircon and baddeleyite record old ages because they were not disturbed by later heating events. The abundant occurrence of 3.92, 4.2 and 4.3 Ga ages at multiple landing sites and auxiliary information from samples, geological data and modeling of ejecta distributions, suggest that these age clusters reflect basin forming impacts.