THE LATEST VIEWS ABOUT LATE ACCRETION. Richard J. Walker and Katherine R. Bermingham, Department of Geology, University of Maryland, College Park, MD 20742; rjwalker@umd.edu

Introduction: "Late accretion" is a term that is widely used in the planetary community, but has come mean different things to different investigators. It is a concept that was created in the 1960's to explain the apparent overabundance of highly siderophile elements (HSE) in Earth's mantle relative to what would be expected from metal-silicate partitioning known at the time. It refers to accretion that occurs subsequent to the cessation of core segregation. In the case of Earth, the total mass of late accreted materials would need to equal or exceed ~0.5 wt.% of Earth's mass to account for the HSE present in the mantle [1-2]. The idea is that as long as metal is extracted from the silicate shell of a planetary body into a growing core, HSE abundances would remain extremely low as a result of the strong preference for these elements to enter metal compared to silicate. Thus, additional accretion would be needed to account for the abundances of these elements. In addition to supplying HSE to the mantle, numerous studies have also invoked late accretion as a means to deliver volatile-rich and organic-rich material to Earth's mantle as well as the mantle of the Moon [3]. Some have envisioned this process as a consisting of a gentle rain of carbonaceous chondrite material that formed a "late veneer". Some studies of HSE in mantle-derived komatiites on Earth have interpreted changes in projected source concentrations with time to indicate a downward mixing of this putative veneer over ~1 to 2 billion years [4].

The concept of late accretion has strengthened somewhat over the years as new geochemical data and dynamical models have provided compelling evidence for the process. For example, Os isotope and relative abundances of most HSE projected for the bulk silicate Earth (BSE) appear to be within the range of chondritic meteorites. These characteristics are difficult to explain by indigenous processes. Nevertheless, some experimental studies of metal-silicate partitioning have discovered conditions (normally at high temperatures and pressures) at which the HSE become less highly siderophile and might conceivably explain the abundances of at least some HSE in the mantle by metal-silicate segregation at the base of a deep terrestrial magma ocean [5]. Given the rapidly growing evidence for and against late accretion, it is valuable to re-assess the concept.

Evidence For and Against Late Accretion: Although frequently forgotten, Os isotopes continue to be the strongest evidence for late accretion. They leave little wiggle room with respect to the precisely chondritic relative abundances of Re-Pt-Os in the bulk silicate Earth (BSE). Conversely, Ru/Ir and Pd/Ir ratios estimated for the BSE are not perfect matches to chondritic meteorites [6], and may indicate that either our ability to estimate BSE ratios from upper mantle materials is not as good as we wish to believe, or that additional processes may have been involved, such as the generation of a Hadean sulphide matte [7]. Alternatively, these ratios may also mean that late accretion was not the process that dominated their abundances in the mantle.

Other bodies provide some supporting evidence for late accretion as a major process in the planetary accretion process. Comparative Earth-Moon mantle abundances of HSE, together with the ~25 ppm difference in $^{182}W/^{184}W$ between the silicate shells of the two bodies provides evidence for stochastic late accretion, whereby late accretion to Earth was dominated by a small number of Pluto mass bodies [8]. This conclusion, coupled with recent dynamical modeling of impactors of that size, suggests that late accreted materials may have been forcefully injected into the mantle with mantle and cores separating, and should not be thought of as having formed a "veneer" [9]. Further, Os isotopes and HSE abundances of mantle-derived rocks from Mars are quite similar to terrestrial compositions and suggest a similar late accretionary process was responsible for establishing the abundances of HSE in the mantle of another, albeit much less massive planet.

New Concepts Injected Into Old Ideas: Warren [10] divided planetary materials into carbonaceous chondrite (CC) and non-carbonaceous chondrite (NC) groups based on mass independent genetic isotopic signatures of lithophile elements such as O, Ti and Cr. The mass independent isotopic compositions of these elements vary among meteorite groups as a consequence of either their parent bodies incorporating varying proportions of presolar materials (Ti, Cr), or by incorporating variable proportions of materials that had been isotopically modified by photochemical processes in the nebula (O). It has been presumed by some that the CC group, consisting of carbonaceous chondrites, as well as some iron meteorite groups, formed in the outer solar system, perhaps beyond the orbit of the proto-Jupiter [11].

One of the most exciting advances in understanding late stages of planetary accretion during the past 10 years comes from the application of isotopic genetic tracers based on siderophile elements, especially the HSE Ru and the moderately siderophile element Mo. As with the lithophile element genetic tracers, Ru and Mo can be used to distinguish between NC and CC groups. As originally noted by Dauphas et al. [12], and referred to as the "cosmic correlation", Ru and Mo isotopic data for most meteorites plot along a linear trend, with carbonaceous chondrites and CC irons plotting at one end, and data for NC meteorites extending along the linear trend, terminating at the terrestrial composition. Data for our work on iron meteorites are shown in Fig. 1.

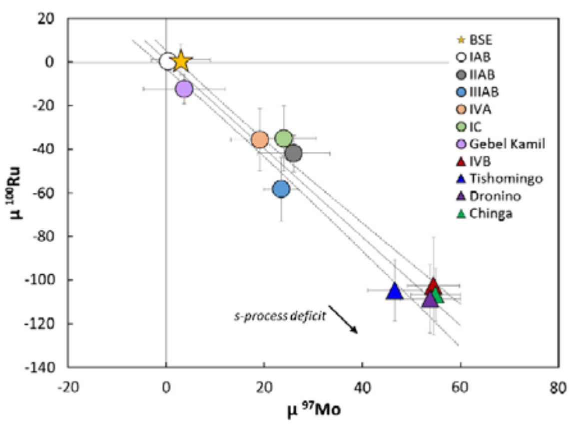

Figure 1. The Mo–Ru cosmic correlation defined by μ^{97}Mo and μ^{100}Ru for iron meteorite groups and individual meteorites. All data were corrected for cosmic ray exposure, and all data were also collected from the same ~ 2cm portions of the meteorites. The circles denote NC groups and the triangles denote CC groups, defined by Mo isotopic compositions. The solid black line is the linear regression through the data and the error envelop is indicated by the gray dotted lines. From Bermingham et al. [13].

Two important findings are revealed from these data. First, the Ru isotopic composition of the BSE is at the opposite end of the trend from CC group meteorites. This means that the dominant component of the putative late accretion *could not have been carbonaceous chondrite-like material*. Thus, unless there are as yet unidentified water/organic-rich NC group meteorites, late accretion could not have been the process that delivered much of Earth's water and organic molecules.

Second, again as originally noted by Dauphas et al. [12], the fact that the Ru-Mo isotopic compositions of Earth lie along the cosmic correlation means that the major final building blocks of Earth did not substantially change from the final 10-20% of accretion that provided the Mo to the mantle, to the final ~0.5% of (late) accretion that provide the Ru to the mantle. Otherwise the BSE would not plot along the now well-defined trend.

It will be important to explore the genetic signatures of materials added to the terrestrial planets at the tail end of the late accretion process, which some have proposed to have been a terminal cataclysm or terminal bombardment. Siderophile element isotopic studies of lunar impact melt rocks and soils will ultimately reveal whether the genetic characteristics of the latest stage of major accretion remained the same as during the preceding 10-20% of accretion.

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