THE COLLAPSE OF THE TERMINAL CATACLYSM PARADIGM…AND WHERE WE GO FROM HERE

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Introduction: At the LPI-sponsored October 2018 conference on Early Bombardment, a broad consensus agreed that the "classic" 45-year-old paradigm of "terminal cataclysm" or "late heavy bombardment" (abbreviated "LHB") is now "off the table." According to that paradigm, a cataclysmic, bombardment, preceded by relatively insignificant cratering, formed most of the moon's large multi-ring impact basins during a ~150 Ma interval ~3.9 Ga ago. It thus seems fair to state that a crucial paradigm of planetary science has collapsed. This collapse is important not only to our field, but also to associated disciplines, including biology. The following is based on an epistemological study of the evolution of the paradigm, completed at the International Space Science Institute, Bern, during 2015-2018 [1].

The Paradigm (1974-2005). The terminal cataclysm paradigm arose, in part, because of pre-Apollo views that lunar rock samples would provide a complete record of Earth-Moon and planetary history [e.g. 2]. As astronauts and Russian Luna probes returned samples, the radiometric dating community thus expressed surprise about a paucity of dates prior to ~4 Ga ago. Two separate groups in 1973, (the Wasserburg group at Cal Tech and Turner/Cadogan in U.K.) simultaneously suggested that some sort of global cratering cataclysm at ~3.9 Ga ago formed most lunar basins at that time (3,4,5,6). Ironically, the Wasserburg group (Tera et al.) initially suggested that the cataclysm might relate to the Imbrium impact [3], probably closer to the emerging modern view, but they later abandoned that idea in favor of some sort of global metamorphic disaster. The term "late heavy bombardment" (LHB) was apparently introduced by Wetherill in 1975 [7,8], but he defined it as identical to the "terminal cataclysm" concept of the Wasserburg group [3,4]. (I speculate that Wetherill may have been trying to avoid the term "cataclysm," which in those days was frowned upon by "uniformitarian" geologists ever since the days of Hutten and Lyell, ca. 1800-1840.) Wetherill sought ways to delay the supposed intense bombardment from planet accretion (4.5 Ga ago) until ~4.0 Ga ago.

A crucial next step in the support of the paradigm was a 1990 study by Ryder [9], demonstrating a huge spike in the age distribution of Apollo *impact melt* rocks, at ~3.75 to ~3.9 Ga ago, with very few impact melts before that. Ryder added a vigorous argument for what I've called "Ryder's rule," that lack of impact melts = lack of impacts. His work was widely accepted as confirming that the early solar system saw ~600 Ma of very few impacts, followed by a cataclysmic spike in multi-ring basin formation at ~3.9 Ga ago.

Another major step in support of the paradigm was valuable work by Cohen et al., involving radiometric dating of impact melt clasts in lunar meteorite breccias. The title of their first paper, in 2000 in Science [10], began with the words "Support for the Lunar Cataclysm Hypothesis." Their data, however, showed no anomalous peak at 3.9 Ga. Their support for the paradigm was thus based on the paucity of impact melts before ~4.0 Ga, and on "Ryder's rule," which assumed that lack of impact melts = lack of impacts.

Skepticism (1973-present). Doubts about terminal cataclysm began as early as 1973-74 [11-14], based in part on pre-Apollo evidence of intense, declining bombardment in the pre-mare era (>3.6 Ga ago) [15-16] --- contrary to minimal impacts then. Hartung [11] pointed out in 1974 that such an impact flux (with increasing survival rates) could produce the appearance of peak in rock survival rates (an idea resurrected by Boenke et al. in 2016 [17]. Additional criticisms [12-16] equated lack of impact melts merely with lack of impact melt *survival*. Intense bombardment before 4.0 Ga ago could thus have pulverized impact melt lenses below multi-ring basin floors on 10^8 year timescales, while allowing modern-day deep, large craters to eject primordial crustal rocks from the base of a megaregolith.

Dynamical models (2000-present.) The terminal cataclysm/LHB paradigm was so well accepted by the early 2000s that dynamical numerical models for the next decade were devoted to explaining the assumed absence of cratering ~4.5 to ~4.0 Ga ago, with a cratering spike at 3.9 Ga ago. The famous Nice model, with its bombardment spike at 3.9 Ga, was presented as a solution [18], based on giant-planet migration models. It was widely accepted as another "proof" of the paradigm --- but as was stated clearly by the authors, it had no physical constraint on the date of migration. Thus, it merely *assumed* that migration started ~3.9 Ga ago, in order to fit the paradigm.

After ~2005, to answer the critique that lunar and asteroidal meteorite data showed no impact spike at 3.9 [13], numerical modelers reversed course and appealed to various effects to explain the *lack of a bombardment spike at 3.9*. Resulting models began to replace the previously "explained" spike [18] with a milder, more gradual surge. For example, in three successive years, 2010-2012, Bottke and co-workers [19-21] presented models extending the spike from its original ~150 Ma, duration, first to 210 Ma (2010), then to 400 Ma (2011) then to a gradual, 1600 Ma surge in impacts at 4.1 to 2.5 Ga ago 2012). Interestingly, a major model by Morbidelli et al. (2018) arrived at a stepwise but essentially monotonic decline in impact flux, starting with an intense initial flux --- thus returning to the initial pre- and post-Apollo suggestions of an early, intense, declining bombardment [12, 15].

In addition to the infelicity of the published (but premature?) model results being variable (and inconsistent), a more serious infelicity occurred, in terms of scientific communication. Namely, these models [19-22] typically referred to their results as "LHB," even though their scenarios became radically different from the original meaning of "LHB" (i.e. a dramatic bombardment spike lasting only ~150 Ma). To be clear, the term "LHB" was diluted to mean whatever results were given by the current model *du jour*. This has caused confusion in other scientific communities, especially among biologists, who, reasonably, expected "LHB" to mean what it meant some years ago. Recent biological still cite "LHB" as a constraint on the origin of life (see [1]).

Where do we go from here? The ghost of the pre-Apollo views, that lunar rocks preserve lunar history since 4.5 Ga ago, still haunts lunar sample interpretation. However, empirical results must prevail over theory (in spite of a recent tendency to discuss and debate models as if they were a more important representation of nature than nature itself.) Among empirical findings: *average* lunar bombardment before ~3.6 Ga ago drastically exceeded later bombardment [15]; most lunar surface rock samples in modern geologic time have survived meteorite "sandblasting" for only some 10^8 years [23-26]; and GRAIL data [27] suggest kilometers (possibly tens of kilometers) of megaregolith, whose formation that could have pulverized pre-4.0 Ga impact melts, while still allowing current excavation of primordial crustal igneous rocks by the deepest recent craters [1]. In short, megaregolith evolution is a key to sample interpretation. The bombardment history of planetary bodies, with fragmentation and megaregolith production, acted as a filter on the age distribution of today's solar system samples. Further research along those lines may provide a clearer, "post-LHB" understanding of lunar and planetary sample interpretation. It seems likely that pre-4.0 Ga megaregolith formation on the moon (and other worlds) converted near-surface melt lenses under the floors of the earliest impact basin into tiny clasts in breccias, which were then mostly covered by mare lavas, ca. 3.8 to 3.2 Ga ago. Other impact melts from these basin impacts, however, were scattered immediately in basin ejecta blankets; still others were ejected and scattered by later Copernicus-sized craters penetrating through basin-floor maria. Tiny clast-fragments of these pre-4.0 impact melts are now being reported in lunar upland breccias.

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