REVIEWING “TERMINAL CATACLYSM:” WHAT DOES IT MEAN?

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Introduction: The idea of an early intense bombardment of the moon can be traced back at least to the 1960s [1], and the more specific concept of a terminal cataclysm dates from ca. 1973 [2,3]. Since then, the term “terminal cataclysm” (or an equivalent term) has been used in many papers as if it were a well-defined, empirically confirmed phenomenon. The meanings attached to this concept, however, range all over the map, from a global metamorphic event, or a 150 Ma-long spike in cratering centered at ~3.92 Ga ago, to still other concepts, such as few impacts before 3.9 Ga ago. Here, we argue that this semantic imprecision has hurt our understanding of the solar system.

History of Concepts*:* Various concepts have been discussed.

** In 1966, Hartmann [1] showed that the average cratering rate before ~3.6 Ga (evidenced in the lunar highlands) had to average ~150-200 times the average rate since then.

** Tera et al. in 1973-4 [2,3] based on Apollo rock samples, proposed a global “terminal cataclysm” metamorphic event at ~3.9 Ga ago, to explain paucity of earlier rocks. They suggested it might involve either the Imbrium basin impact around 3.9 Ga ago, or a clustering of many impact basins around that time.

** Hartmann, in 1975 [4], argued that a unique cataclysmic event at 3.9 Ga might be a “misconception” and that absence of early samples might involve more uniformitarian cratering, but so intense before ~ 4.0 Ga that earlier rocks were reset in age or lost by pulverization.

** The concept of “late heavy bombardment,” (“LHB”) at 3.9 Ga gained wide acceptance in 1990 when Ryder [5] showed that a huge spike in Apollo impact melt ages centered around 3.85-4.0 Ga ago. He also argued, importantly, that relative lack of impact melts from ~4.4 to 4.0 Ga indicated lack of impacts in that period.

** Circa 1998, Haskin, Korotev, and co-workers [6] argued that prevalence of ~3.9 Ga dates involved KREEP-rich ejecta from the Imbrium impact at that time, present at several Apollo sites. This was controversial, but echoed one of the proposals of Tera et al. in 1974.

** In 2000, Cohen, Swindle, and Kring [7] began reporting dates of impact melt clasts in KREEP-poor lunar meteorites. Their data show no Ryder-like spike at 3.9 Ga. Nonetheless they inferred “Support for the Lunar Cataclysm Hypothesis” (from their title), citing Ryder’s rule, that lack of impact melts = lack of impacts, so that impacts must have started with a burst around 4.0.

** In 2001, Stöffler and Ryder [8, Table VI) estimated impact ages (at least 2 values each) for 5 basins. Here I add their 1σ error bar to their high value and subtract it from their lowest value, and list the average resulting value in brackets. Expressed in Ga, they give: Orientale 3.72-3.85 [3.785]; Imbrium 3.75-3.87 [3.81]; Crisium 3.80-3.91 [3.855]; Serenitatis 3.84-3.90 [3.87]; Nectaris 3.80-3.95 [3.875]. Thus they pack major basins with a wide range of crater density into an interval ~ 90 Ma, and no more than 230 Ma at 1-sigma levels. This work encouraged the idea that radiometric data had proven the existence of a terminal cataclysm.

** In 2003, Hartmann [9] argued that the Cohen data plus asteroidal meteorite data conflicted with the concept of a global lunar terminal impact cataclysm at 3.85-4.0, since their data show no sharp spike of impacts at that time.

** Around 2005 dynamicists introduced the “Nice model,” in which outer solar system resonance effects scattered a wave of planetesimals into the inner solar system [10]. By assuming that this happened at 3.9 Ga, they argued that the dynamical model explained the LHB. These models showed few impacts during 4.4 to 4.0 Ga, supporting Ryder’s rule. The title of [10] directly linked “Origin of the cataclysmic Late Heavy Bombardment period” to the Nice model. This work encouraged the idea that the Nice model had confirmed the LHB concept.

** By 2011, Norman and Nemchin [11] and others reported increasing numbers of pre-4.0 Ga impact melt dates, e.g. ~4.2 and ~4.33, from upland breccias. This refuted Ryder’s rule that no large impacts happened before 4.0 Ga ago.

**After ~2011, dynamical models responded by moving away from a sharp spike at 3.9 Ga, for example introducing sawtooth spikes before 4.1 Ga, and a drawn out decline after 3.8. The latter decline was supported by earlier cratering data from Hartmann and Neukum [12]. In 2014, Marchi, and co-authors including Bottke, Morbidelli, and Kring [13, Fig. 1], presented new calculations of impact rates from scattered asteroids, showing a smooth decline in cratering from 4.4 to 4.0 Ga, which matched (unmentioned) curves based on cratering data, published as early as 1970. However they still proposed that an LHB could be added to their curve.

Current Status of Terminal Cataclysm. Today, growing indications that the putative massive scattering of outer solar system objects into the inner solar system 3.85-4.0 Ga ago never happened, since no Ryder-like spikes are observed in asteroidal or lunar meteorite data. Similarly, the concentration of basin scale impacts at 3.78-3.88 Ga ago is dubious, not only because 4 out of the 5 "dated" basins have inadequate samples from rim structures or ejecta, but also because we now have impact melt concentrations at ~4.2 Ga and earlier.

Thus, the terms "terminal cataclysm," "late heavy bombardment", "LHB," etc., though still commonly and casually used by scientists and journalists, have evaporated into nothing that has a clear, verifiable meaning. Perhaps it is time to end the use of these terms unless clear definitions and better evidence are provided. As stated in [11], "The strong version of the late cataclysm hypothesis in which all of the lunar basins formed between 3.8 and 4.0Ga (Ryder, 2002; Gomes et al., 2005; Abramov and Mojzsis, 2009) appears untenable."

Hypothesis for Explaining the Age Distribution of Lunar and Asteroidal Sample: As reviewed by Neukum et al [12], reconstructions of the curve of cratering rate vs. time, based on Apollo and Luna samples, even as far back as 1970 [14], show that the impact rate 3.8-3.9 Ga ago was of order 150-200 times the present rate, but declining rapidly. As shown in [9, 15], this was sufficient to cause much more rapid growth of regolith (and mega-regolith) than in the last 3.6 Ga. The general idea [4, 9, 15] is that around 3.8 to 4.0 Ga ago, an interval as short as 50-100 Ma was adequate to create many 10s of meters of pulverized material. This alone shows that samples earlier than 4.0 Ga should be hard to find, as observed in the early 70s by Tera et al. [2,3].

But a more subtle, profound, and under-appreciated effect is involved (9,15), involving the size-frequency distribution (SFD) of craters. If we slightly extrapolate the published impact rate-vs time backwards to the 4.0-4.1 Ga era along the curves published by Hartmann [14], Neukum [cf. 12], and most recently by Marchi et al. [13], we find that around 4.0-4.1 Ga ago, new surfaces became saturated with all craters in the diameter range of 2 to 100 km simultaneously, within ~100 Ma after their formation. Therefore, the period from 3.9 to 4.1 Ga ago (and probably before) marks a critical era, in which megaregolith ate into the lunar crust to depths of kilometers in short intervals of order 100 Ma or less. If we accept any steeply declining curve of impact flux vs. time, with a shape of form shown by in published curves from 1970 [14] to 2014 [13], then we can say that rocks older than 3.9 to 4.1 Ga would be hard to find, as per [2,3].

A still more subtle effect explains why pre-4.1 impact melts are more scarce than pre-4.1 igneous rocks. The largest volume of impact melts was contained in a modest number of localized impact melt lenses, with different ages, in the upper kilometers of the largest basin floors. Intact samples of the magma ocean igneous crust, however, exist below the megaregolith everywhere on the moon. Thus, if the megaregolith in the first 600 Ma rapidly reached depths of a few km, then the impact melt lenses may have been mostly converted to small clasts in upland breccias, and few impact melts older than 3.9 Gy are broadcast upon the lunar surface in recent time by "Tycho- or Copernicus-scale impacts" --- but those same sized impacts can tap into sub-megaregolith igneous crust.

As discussed in [9], this model is consistent not only with lunar observations, but also with asteroidal meteorite data.

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