UNDERSTANDING THE EFFECTS OF ASTEROID COLLISIONS ACROSS EARTH'S GREAT OXIDATION 3.5-2 Ga. Simone Marchi[1], B. Black[2], N. Drabon[3], D. Ebel[4], R. Fu[5], B. Johnson[6], T. Schulz[7,8], K. Wuennemann[9], [1]Southwest Research Institute, Boulder, CO (marchi@boulder.swri.edu), [2]City University of New York, New York, NY; [3]Stanford University, Stanford, CA; [4]American Museum of Natural History, New York, NY; [5]Harvard University, Cambridge, MA; [6]Brown University, Providence, RI; [7]University of Vienna, Vienna, Austria; [8]University of Cologne, Germany; [9]Natural History Museum, Berlin, Germany.

Introduction: Advances have recently been made in understanding the nature and rate of collisions between the Earth and planetesimals left over from planet formation (e.g., [1-3]). This work suggests that while life was emerging and evolving, the Earth was subject to cosmic collisions that may have fundamentally modulated the ensuing geochemical evolution of the biosphere. Of particular interest is the evolution of the biosphere during the Archean and Paleoproterozoic (~3.5-2 Ga), which was punctuated by drastic environmental changes, such as the rise of atmospheric oxygen at ~2.4 Ga (e.g., [4]). Although early Earth collisional models are uncertain, the geological record retains strong evidence for the occurrence of large collisions during this time, as witnessed by the numerous impact spherule layers 3.4-2.4 Ga. As a reference, the estimated individual energy of these collisions ranges from a few times to ~500 times that of the Chicxulub impact. The causal connection of the Chicxulub impact with the Cretaceous-Paleogene (K-Pg) mass extinction at ~66 Ma is the best known example of the effects of collisions on the biosphere. The energy range of the impacts recorded in the spherule layers underlines their potential repercussions on early environments.

Large collisions are associated with localized environmental havoc. Global scale environmental changes, however, are less understood (e.g., [5-6]). For example, impact melting and vaporization of target and projectile materials can lead to outgassing with poorly understood consequences for the redox state of the atmosphere and oceans. Collisions also deliver and mobilize key nutrients in the crust (e.g., Ni, P, Fe). Through such processes, collisions may have shaped the short and long term evolution of the Earth's biosphere (Fig. 1). In this light, it is important to consider whether and how collisions altered habitability of the Archean and Paleoproterozoic Earth.

Revising the terrestrial asteroid impact flux 3.5-2 Ga: In recent years, the intensity of bombardment in the Earth-Moon system during the Hadean-Eoarchean (>3.5 Ga) has been subject to intense debate. A combination of geophysical observations, geochemical data, and dynamical models have been used to constrain the combined Earth-Moon collisions history (e.g., [1,3,7,8]).

Subsequent late Archean and Paleoproterozoic bombardment (~3.5-2.0 Ga), however, has been poorly investigated due to the paucity of observational constraints. For instance, the oldest known terrestrial crater is the 300-km Vredefort structure, ~2 Ga; while there are no available lunar absolute calibration sites in the time frame ~0.8-3.1 Ga. The Archean is an interval in Earth history where massive collisions (> 100 km in diameter) likely gave way to smaller but still sizable impactors (~10-100 km). The stochastic nature of the bombardment associated with a declining flux may have resulted in a few massive collisions (~100 km).

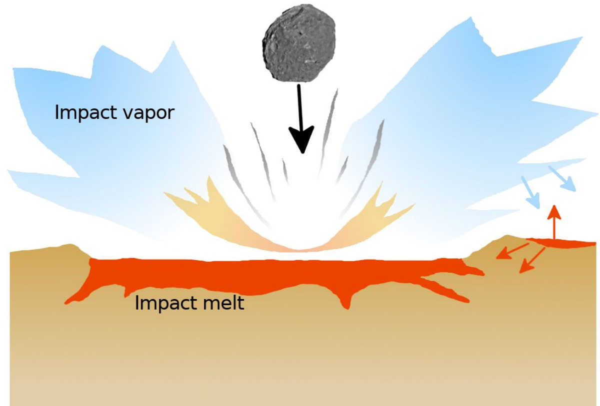

Figure 1. Schematic view of impact meting (red) and vaporization (blue) with consequences on atmospheric redox, and hydrothermal migration of key redox elements and nutrients to the environment (schematically indicated by blue and red arrows).

Crucial constraints can be obtained from direct records of collisions, such as impact spherule layers. The spherule layers probably represent an incomplete record of impacts during this time interval (e.g., [9]); however, they do provide a useful lower limit for the bombardment flux.

There are currently 16 known impact spherule layers identified in outcrops in the 3.5-2.0 Ga time range, some of which have only very recently been discovered (Fig. 2). Additional spherule layers have been found in drill cores, however, it remains unclear whether they represent new, independent impacts or are duplicates of known spherule layers [10-12].

We will present an updated list of spherule layers and corresponding impactor sizes, based on the methods proposed by [13]. This method relies solely on aggregate spherule layer thickness, and it has been shown to provide realistic results for the K-Pg layers and Chicxulub impact [13]. As an example, a spherule layer aggregate thickness of 10 cm yields projectile diameters from ~29 to ~46 km, and the projectile diameters from Archean and Paleoproterozoic spherule layers range from 10 to 80 km.

In addition, the impactor sizes corresponding to the spherule layers will be used to calibrate available collisional models (e.g., [1,3]). The resulting calibrated impact flux for the Archean and Paleoproterozoic will provide the basis for subsequent investigations of the environmental consequences of these collisions.

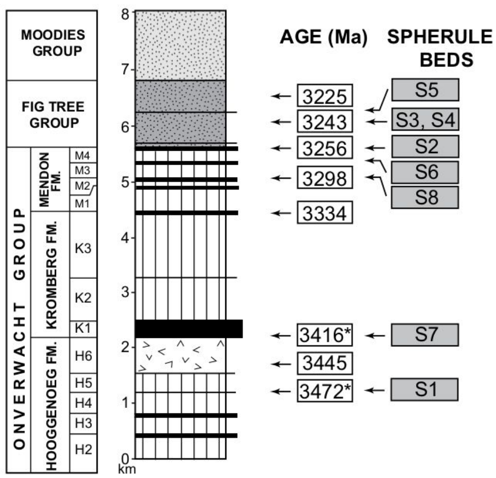

Figure 2. Main impact spherule layers discovered in outcrops in the Barberton Belt, South Africa. The newly discovered layers are indicated with S4-S8. Main stratigraphic units and their ages are also shown. The figure is adapted from [14].

Environmental effects of asteroid collisions: The Earth experienced several major shifts in its surface environments from 3.5-2 Ga, including possible whiffs of oxygenation in the runup to the Great Oxidation Event at ~2.4 Ga (GOE [4]). The oldest preserved evaporates date to ~2 Ga, documenting the establishment of a significant reservoir of surface oxidant in the form of sulfates by that time [15]. The role of volcanism and the shifting redox of volcanic gases (e.g., [16,17]) in regulating the oxygenation of surface environments has been discussed. However, the contribution of declining fluxes of strongly reduced impact vapors (e.g., [18]) remains to be assessed.

In this contribution we will outline and discuss the overall effects of impact vaporization of both target and projectile materials on atmospheric chemistry. Consider the following examples. In an impact with a 100-km projectile, and assuming that 25% of the projectile is vaporized [19], we expect $\sim 3\times10^{17}$ kg of gas (for an impactor density of 2600 kg/m^3, representative of ordinary chondrite-like asteroids). For context, the modern atmosphere has a mass of $\sim 5\times10^{18}$ kg. Global natural methane emissions total $\sim 1.5\text{-}3.0\times10^{11}$ kg/year (e.g., [20]). Based on calculations for equilibrium with a chondritic projectile [18], 25% vaporization of a 100 km CI chondrite bearing ~3 wt% C [21] translates to $\sim 10^{16}$ kg of CH_4 delivered nearly instantaneously. Given the fluxes of vapor involved, and assuming a similar atmospheric density in the Archean, a 10-100 km projectile can dramatically perturb atmospheric composition.

In addition, hydrothermal alteration of impact melts may produce significant fluxes to surface environments of Fe, P, and trace elements such as Cr, Mo, Ni. Shifts in availability of key nutrients including Ni have been invoked to explain the structure of Archean redox evolution (e.g., [22]). Fluctuations in the concentrations of redox-sensitive trace elements, such as Cr and Mo, in marine sediments have been applied as tracers of Earth's oxygenation history. To correctly understand and interpret potential nutrient sources in Earth's Archean and Paleoproterozoic oceans and to assess the implications of impact melt emplacement for interpretation of seawater trace element records, improved constraints are needed on potential fluxes of both nutrients and trace elements from hydrothermal alteration of impact melt.

Discussion: In this contribution, we will aim to present a revised terrestrial impact flux 3.5-2 Ga. This constitutes the prerequisite for further investigations attempting to study the environmental effects of Archean and Paleoproterozoic collisions.

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