LARGE IMPACTS ON THE EARLY EARTH: PLANETARY STERILIZATION AND IRON DELIVERY.
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Introduction: During the tail-end of accretion the early Earth experienced a large number of impacts that could have either inhibited or increased early habitability. Impacts of sufficiently large scale could have sterilized the early Earth, and the timing the the last sterilizing impact constrains the timing of the emergence of precursors to life as we know it [1]. Alternatively, it has been suggested that large impacts were critical to the emergence of life, delivering iron required to create a reducing environment favorable to the development of RNA precursors [2, 3]. Despite the importance of large (diameter D = 1000-3000 km) impacts to early habitability, only limited studies [*e.g.*, 4, 5] have explored the detailed effects of such impacts. Here we present 3D numerical simulations of impacts on the early Earth in order to better quantify the effects of such impacts on planetary habitability. We quantify which impact events would be globally sterilizing and which would deliver sufficient iron to the surface to promote a reducing environment.

Methods: We modeled 3D impacts on the early Earth using the Gadget-2 SPH code [6]. We used an updated version of the ANEOS equation of state with new parameters for forsterite and Fe-Si iron alloy to model the planetary mantle and core, respectively [7, 8]. We conducted a set of simulations varying impactor mass (0.0012, 0.003, 0.006, or 0.012 M_{Earth}; D = 1500, 2000, 2700, or 3400 km), impact velocity (1.1, 1.5, or 2 v_{esc}), and impact angle (0, 30, 45, or 60°). The impactor and target both had core mass fractions of 0.3. An example simulation is shown in Fig. 1.

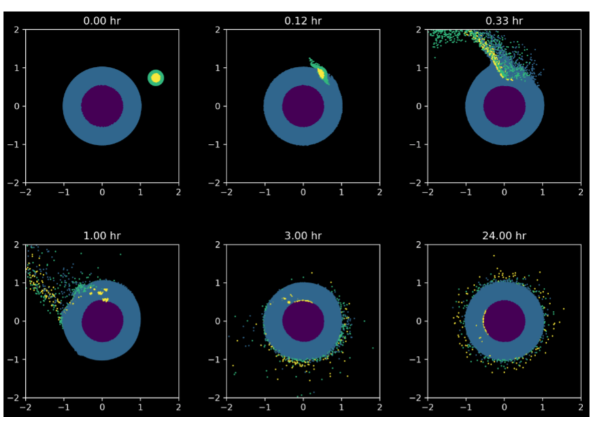

Figure 1: Example simulation of a 0.006 M_{Earth} projectile impact a protoearth target at 1.5 vesc and θ=60°.

Sterilization: Impact sterilization has been proposed to result from either global impact-induced melting of the near surface [9] or vaporization of the pre-impact ocean by the hot impact generated rock vapor atmosphere [1]. We examine surface melting by determining the equivalent melt depth in the surface layer of SPH particles (Fig. 2). We find that impacts >0.006 M_{Earth} generally delivery enough energy to melt most of the surface, while impacts 0.003 M_{Earth} only partially melt (sterilize) the surface. Lower velocity and more grazing impacts also cause less surface melt.

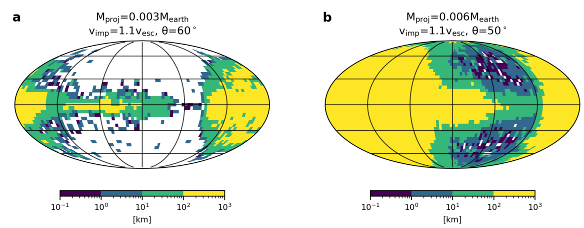

Figure 2: Examples of surface melting for two different simulations. Filled contours correspond to the equivalent melt depth in the outer layer of particles.

Vaporization of the pre-impact ocean is examined by determining the amount of energy contained in the impact generated hot rock vapor atmosphere. We compute the number of oceans the atmospheric energy could vaporize if all of its energy went into ocean vaporization; this is an upper limit as the atmosphere would radiate both outwards and downwards onto the planetary surface [1]. We find that about 2-10% of the impact kinetic energy goes into the internal energy of the impact-generated atmosphere. Vaporization of an ocean's mass of water is unlikely for a 0.0012 M_{Earth} impact but could occur as a result of a 0.003 M_{Earth} impact, depending on the impact angle and velocity.

Iron delivery: The early Earth is expected to have a more oxidizing atmosphere, making the generation of a transient reducing atmosphere via the impact delivery of iron critical to generating an environment favorable for RNA synthesis [2, 3]. Late delivery of iron is expected based on the excess concentration of highly siderophile elements in the Earth's mantle and could be delivered by a single impact of a lunar-sized body $D \sim$ 3400 km [5, 10].

We find that the majority of projectile iron is delivered to the mantle. Only a small portion of the projectile iron is delivered to the surface or vaporized into the atmosphere. Iron delivered to the atmosphere would relatively quickly rain out and be available to reduce any surface water. For a given impact, the mass of surface iron and bound iron vapor give a rough estimate of how much water can be reduced by the impact-delivered iron, as shown in Fig. 3. This estimate is an upper bound because if iron rains out over surface melt it may quickly be sequestered into the solidifying crust where it could remain unavailable to participate in reduction of the steam atmosphere. To account for this we also report the amount of water reduced by iron that rains out only over unmelted surfaces (Fig. 3).

In general, insufficient iron appears to be delivered to the surface and atmosphere to reduce an ocean's mass of water from a single impact. While larger impacts do deliver sufficient iron to reduce an ocean's mass of water, much of this rains out over melted surfaces which encompass more of the planet in the aftermath of larger impact events.

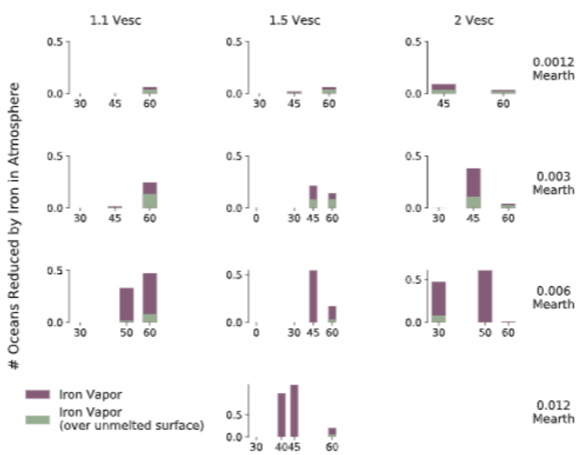

Figure 3: Number of oceans that could be reduced from projectile iron delivered in large impacts. Columns and rows correspond to impact velocity and mass, respectively, with bar charts subdivided along the x-axis according to impact angle.

Discussion: Our results build on prior studies of early Earth impacts [*e.g.*, 4, 5] by exploring both impact sterilization and iron delivery over a large parameter space in 3D geometry with updated equations of state. For impact sterilization we find that 0.003 M_{Earth} (D = 2000 km) impacts are insufficient to sterilize the Earth through global melting of the surface but may cause sterilization by global ocean vaporization, depending on the impact parameters. For iron delivery we find that most projectile iron is incorporated into the Earth's mantle. Delivering sufficient iron to reduce an entire ocean's mass of water from a single impact is difficult. Even if the impact were sufficiently large (D = 3400 km) to deliver enough iron to the atmosphere, much of this iron would rain out over a molten rock surface and may be unavailable to participate in the subsequent reduction of surface water (which is supercritical in the ocean-vaporizing regime).

One consideration that may affect these results is the inclusion of a material strength model, which can have an important effect on model outcomes at these scales [*e.g.*, 11]. In particular the fluid assumption used in our simulations results in deposited impact energy being spread more evenly across the planetary surface. Inclusion of material strength would localize the deposited impact energy, resulting in a smaller surface area that reaches full melting. This could increase the size of impact necessary to globally melt the surface, and therefore also increase the amount of iron that rains out over unmelted surfaces for a given impact size, overall increasing post-impact habitability. Simulations including material strength are a focus of future work.

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