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# Impact melting of frozen oceans on the early Earth: Implications for the origin of life

J. L. BADA*, C. BIGHAM*, AND S. L. MILLER†

*Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093-0212; and †Department of Chemistry, University of California at San Diego, La Jolla, CA 92093-0317

*Contributed by S. L. Miller, September 7, 1993*

**ABSTRACT** **Without sufficient greenhouse gases in the atmosphere, the early Earth would have become a permanently frozen planet because the young Sun was less luminous than it is today. Several resolutions to this faint young Sun–frozen Earth paradox have been proposed, with an atmosphere rich in $CO_2$ being the one generally favored. However, these models assume that there were no mechanisms for melting a once frozen ocean. Here we show that bolide impacts between about 3.6 and 4.0 billion years ago could have episodically melted an ice-covered early ocean. Thaw–freeze cycles associated with bolide impacts could have been important for the initiation of abiotic reactions that gave rise to the first living organisms.**

## Introduction

Energy balance models have extensively considered the effect of a decrease in solar luminosity on the climate of the Earth (1–7). With the present atmospheric composition, a decrease in luminosity of only a few percent would result in a totally ice-covered ocean, and because of a planetary albedo near that of ice, global surface temperatures would be less than −40°C. An increase in solar luminosity of ≈30% greater than the present value would be required to defrost the planet.

Solar evolution models predict that the young sun was 20–30% less luminous than today (3), which generates the problem of why the Earth did not become a permanently frozen planet early in its history. Although a number of solutions to the faint young Sun paradox have been suggested, the one generally preferred is that the concentrations of greenhouse molecules in the early atmosphere were much higher than at present (see ref. 8 for discussion). For example, $NH_3$ at a volume mixing ratio around $10^{-6}$ would have prevented the freezing of the early ocean (9). This is attractive from an origin-of-life point of view. Ammonia dissolved in the early oceans (as $NH_4^+$) would have been important for both prebiotic synthesis and preservation of amino acids (10, 11). However, $NH_3$ is thought to have been rapidly destroyed in the atmosphere of the early Earth by photochemical reactions (12), and its steady-state atmospheric concentration is generally thought to have been too low to prevent the freezing of the planet. According to this model, dissolved oceanic $NH_3$ required for prebiotic syntheses would have been steadily depleted because of its rapid destruction in the atmosphere.

$CO_2$ concentrations $10^3$–$10^4$ times present atmospheric values would have prevented the formation of an ice-covered ocean on the early Earth (see ref. 8 and references therein). These high levels of $CO_2$ have been dramatically reduced throughout the Earth's history as solar luminosity increased. This reduction could have been associated with the growth and weathering of continents (13), although it is uncertain whether there were any continents prior to 3.8 billion years ago (14). $CO_2$-rich atmospheres have been shown to be inefficient in the prebiotic synthesis of organic compounds (15, 16). The requirement of high atmospheric $CO_2$ to prevent a glaciated early Earth generates a problem with respect to the source of the organics necessary for the origin of life. This has led to suggestions that prebiotic organic compounds were supplied from extraterrestrial sources (17, 18), although the amounts were very small from these sources.

The advocates of the high $CO_2$ early atmosphere admit that this scenario is purely theoretical but consider it to be an important constraint. For example, Kasting (8) states that "Atmospheric $CO_2$ concentrations should have risen to whatever level was needed to keep the oceans from freezing and to balance the global C budget." High $CO_2$ levels in the early atmosphere may have been the direct result of an impact-associated accretion process (13). However, impact erosion of the early atmosphere (19) could have resulted in atmospheric $CO_2$ concentrations insufficient to prevent the formation of permanently frozen ocean. In addition, feedback mechanisms associated with reflective $CO_2$ clouds could have resulted in surface temperatures less than the freezing point of water and thus a glaciated Earth (20). Given the uncertainties, the possibility exists that sometime in the early history of the Earth, the oceans were completely ice covered.

## The Early Ocean Would Not Freeze Completely

A totally ice-covered early ocean does not mean that the ocean froze completely because heat flow from the Earth's interior through the oceanic crust would provide a heat source to the ocean beneath the ice layer. To evaluate the ice thickness, we use a simple one-dimensional heat flow model. We assume that the heat flow from the ocean floor in a well mixed ocean provides a heat source to the bottom of the ice layer, and this heat flux is balanced by the heat lost from the ice surface to the atmosphere. The steady-state thickness ($X$) of ice that would thus accumulate is given by:

$$X\ (\mathrm{cm}) = k(T_{\mathrm{ocean\ water}} - T_{\mathrm{ice\ surface}})\mu^{-1},$$

where $k$ is the thermal conductivity of ice ($2 \times 10^{-2}$ $\mathrm{J{\cdot}sec^{-1}{\cdot}cm^{-1}{\cdot}{}^{\circ}C^{-1}}$) and $\mu$ is the heat flow through the oceanic crust (present value, $8 \times 10^{-6}$ $\mathrm{J{\cdot}cm^{-2}{\cdot}sec^{-1}}$). Using $T_{\mathrm{ice\ surface}} = -40°\mathrm{C}$ and $T_{\mathrm{ocean\ water}} = -2°\mathrm{C}$ gives an ice thickness of ≈1 km. On the early Earth, the heat flow was likely ≈3 ± 1 times greater than the present value (13, 21). Thus, the ice thickness would have been only 300 ± 100 m.

## Impact Melting of an Ice-Covered Early Ocean

A way around the once frozen/always frozen ocean dilemma, and to still allow modest $CO_2$ atmospheric levels, is to melt the frozen oceans by bolide impacts. Bolide impacts have been suggested to have frustrated the origin of life because of

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their frequent occurrence on the early Earth and their devastating effects such as the total vaporization of the early ocean and sterilization of the planet (22, 23). Adopting the value of Sleep *et al.* (23) that 25% of the impact energy of a large bolide would be globally distributed as thermal energy (the rest of the energy is buried at the impact site or lost to space), we can calculate the size of the object needed to melt an ice layer on the early ocean. The diameter ($d_{\mathrm{melt}}$) of an ice-melting bolide is given by:

$$d_{\mathrm{melt}}\ (\mathrm{cm}) = 5.3 \times 10^2\{Q\rho_{\mathrm{ice}}H_{\mathrm{f}}X\}^{1/3}\{v^2\rho_{\mathrm{bolide}}\}^{-1/3}$$

$$= 2.9 \times 10^5\ X^{1/3},$$

where $Q$ is the ice surface area (taken as $5 \times 10^{18}$ cm$^2$), $\rho_{\mathrm{ice}}$ is the density of ice (0.9 g·cm$^{-3}$), $H_{\mathrm{f}}$ is the heat of fusion of ice at 0°C (334 J·g$^{-1}$), $v$ is the bolide impact velocity ($1.5 \times 10^6$ cm·sec$^{-1}$), $\rho_{\mathrm{bolide}}$ is the bolide density (4 g·cm$^{-3}$), and $X$ is the ice thickness (cm). If only 10% of the impact energy was globally distributed as heat, the $d_{\mathrm{melt}}$ values would increase by only 36%. The bolide diameters would be ≈25% larger if the entire ice layer was at −40°C. The above equation indicates that bolides with diameters of ≈100 km would have been sufficient to melt the 300 ± 100 m of ice cover on the early ocean. Because of the lower heat of fusion of ice compared to the heat of vaporization of water (2260 J·g$^{-1}$ at 100°C), the bolide size required to melt a 300-m-thick layer of ice is considerably smaller than those needed to vaporize the photic zone and the entire ocean (23).

The impact of small bolides may also have played a role in the melting of an ice-covered ocean. Bolides of $K/T$ boundary size (10 km in diameter) would have struck the Earth much more frequently than those that would melt a 300-m ice layer on the ocean (22, 24). A $K/T$ boundary size bolide would have punctured the ice layer generating a hole hundreds of kilometers in diameter. These small impacts would have permitted the partial escape of gases trapped in the ice-covered ocean (see below). The released gases could have been important in prebiotic chemistry, in the energy balance of the Earth, and in the eventual transition to an unglaciated planet. In addition, holes several hundred kilometers in diameter may have grown in size to the point that the planetary albedo was sufficient to prevent refreezing.

## Periodic Thaw–Freeze Cycles Associated with Impacts

The frequency of impacts of ice-melting bolides has been estimated to be one event every $10^5$–$10^7$ years between about 3.6 and 4.0 billion years ago (22, 24). The lunar cratering record suggests that between 3.9 and 3.8 billion years ago several ice-melting bolides could have struck the Earth (24). If the greenhouse gases in the atmosphere were insufficient to prevent refreezing, there could have been periodic thaw–freeze cycles associated with the ice-melting impacts. Around 3.6 billion years ago, the frequency of ice-melting bolide impacts was approaching the present day value of one event every $10^9$ to $10^{10}$ years (22, 24). At this time, the atmosphere would need to have had a $CO_2$ (or other greenhouse gas) content sufficient to warm the planet above 0°C in order to prevent the Earth from becoming a permanently glaciated planet. Alternatively, the shift in the planetary albedo to a value close to that of water caused by the melting of an ice cover could have been sufficient to prevent refreezing.

The main sources and sinks of atmospheric $CO_2$ on the early Earth are thought to be continental and sea floor weathering reactions and mantle degassing through hydrothermal vents (13, 25). Although surface volcanoes are a significant source of atmospheric $CO_2$ on the modern Earth, this source would have been much less important on the early Earth because of the small continental area. During the frozen periods, $CO_2$ released through vents would remain in the oceans because of the ice cover. The amount of $CO_2$ that would accumulate in the ice-covered ocean would be determined by the time interval between ice-melting impacts and the precipitation of various carbonate minerals. Some of the $CO_2$ would form a clathrate hydrate, which because it is denser than water would have accumulated on the ocean floor. Gases such as $CH_4$, $H_2$, CO, $N_2O$, and possibly $NH_3$ could have been directly released into the unfrozen ocean by hydrothermal vents (26, 27) during the ice-covered period. The impact melting of the ice cover would have rapidly released the gases trapped in the ocean into the atmosphere.

The amount of greenhouse gases stored in the partly frozen ocean would have been critical in determining the future fate of the Earth. If the quantity of greenhouse gases released was insufficient to raise global temperatures above 0°C, the ocean surface would have again become ice covered. The release of excessive amounts of greenhouse gases could have resulted in a runaway greenhouse and a hot Earth. Within the framework of this thaw–freeze model, we surmise that one of the ice-melting bolide impacts, or perhaps one that only punctured the ice layer, released greenhouse gases in sufficient quantities to prevent refreezing of the ocean surface sometime around or prior to 3.6 billion years ago.

## An Ice-Covered Early Ocean and the Origin of Life

Let us now consider the episodic thawing and refreezing of the early ocean from the viewpoint of the synthesis of molecules important in the origin of life. As an example of the type of prebiotic organic reactions important for the origin of life, we will consider the synthesis of amino acids, although it is not known whether amino acids were essential for the first self-replicating systems on the Earth.

The amino acids in carbonaceous meteorites were likely synthesized during aqueous alteration of the meteorite parent body via the Strecker pathway (10, 28–30):

$$NH_3 + \underset{\substack{\text{aldehydes}\\ \text{and ketones}}}{RR'CO} + HCN$$

$$\rightleftarrows \underset{\text{amino nitrile}}{RR'C(NH_2)CN} \rightarrow \underset{\text{amino acid}}{RR'C(NH_2)COOH}$$

where R and R′ are the amino acid α-substituents. Provided the atmosphere was sufficiently reducing to produce the necessary reactants, the Strecker synthesis would have taken place readily in the ocean of the early Earth (10), producing an amino acid concentration perhaps as high as $10^{-4}$ M (16).

On the bases of photochemical arguments, a reducing early atmosphere is claimed to be unlikely (8, 12) and thus other sources and processes are needed to provide the reactants for amino acid synthesis in the early ocean. One possibility is bolide impacts, which might produce components such as $NH_3$, HCN, and aldehydes either from the impact shock synthesis in a neutral or mildly reducing early atmosphere (31) or from the pyrolysis of bolide organics (32). Components such as $NH_3$, HCN, and aldehydes produced during impact would have been rapidly washed from the atmosphere and dissolved in the ocean (31) during the thaw period caused by the bolide impact. In addition, $CH_4$, $H_2$, CO, and $NH_3$ derived from hydrothermal vents would have been stored in the unfrozen ocean below the ice layer. Impact melting would have released these gases into the atmosphere where they would have been important in the formation of HCN and aldehydes. Refreezing of the ocean surface would have trapped the Strecker reactants formed during the thaw period in the oceans where they subsequently would have been involved in oceanic prebiotic reactions such as the Strecker synthesis.

At −2°C, the temperature of the ocean below the ice layer, the stability of organic molecules would have been enhanced in comparison to higher temperatures. Also, in the pH range 7–8 the hydrolysis half-life of HCN to formic acid and $NH_3$ is $10^4$–$10^5$ years at −2°C compared to only a few years at 50°C (16). The steady-state concentration of HCN would thus have been the highest in an ice-covered early ocean. The incomplete freezing of the ocean would provide a way of concentrating components necessary for various prebiotic organic syntheses. However, even with an ice layer 1 km thick, this concentration effect would have been small. More important, surface ice would have protected organic molecules dissolved in the unfrozen ocean below the ice layer from destruction by ultraviolet light.

## Conclusions

We have shown here that the impact of bolides with diameters of ≈100 km would have melted an ice-covered early ocean. The requirement that high atmospheric $CO_2$ levels were needed to prevent the formation of a glaciated Earth is unnecessary. Although bolide impacts may have initially frustrated the origin of life, subsequent impacts could have periodically melted an ice-covered ocean, thereby causing a rapid cascade of reactions that resulted in the origin of the first living organisms. A necessary condition for the origin of life on the Earth and Earth-like planets in other solar systems may be suitably timed bolide impacts to melt the frozen planet. Without ice-melting bolides, life may not originate even though the conditions were otherwise favorable.

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