A Cataclysmic Origin of Life?

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Our Solar System

NASA
The destructive power of impact events

Image: J. Tucciarone
The destructive power of impact events

Data from French (1998)
Annihilation of ecosystems by large asteroid impacts on the early Earth

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Figure: Zellner (2017).

Impact frustration of the origin of life

Kevin A. Maher & David J. Stevenson

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• Growing evidence for life on Earth at \(~3.8\text{–}4.1\text{ Ga.}\)
• Lunar craters: impacts \(~10\text{–}20\) times more common at this time than they are now.
• **Question:** How did life evolve at the harshest, most inhospitable time in Earth’s history?

Image: NASA.
Hypothesis:

Impact craters can generate conditions suitable for the emergence of life through the production of substrates for prebiotic chemistry, through delivery of life-essential elements, and through the production of habitats for microbial life.
The impact cratering record on Earth
Welcome to Impact Earth!

The goal of Impact Earth is to engage researchers and the public alike and in the study of meteorite impacts, fireballs and meteorites in Canada and around the world. We invite you to explore the impact cratering database, which highlights the numerous impact structures around the world, as well as our activities and resources designed for educators from elementary to post-secondary education.

Fireballs

The Earth is constantly being bombarded by the extraterrestrial material, learn about what happens when they enter the atmosphere and break up. Take some time to view the ASGARD All-Sky Camera Network that monitors the sky in southwestern Ontario for fireballs.

Meteorite Database

As one of Canada’s leading research centres, the Centre for Planetary Science and Space Exploration at Western University is home to a collection of nearly 300 meteorites and provides a means for our researchers and students to examine and explore planetary materials and processes. We invite you to explore learn more about are collection!

Activities & Resources

In a continued effort to engage the public and demonstrate the necessity of understanding impact cratering, we have prepared several resources for different levels of education and the general public! We invite you explore are various resources and help advance our understanding of the impact cratering process.

Impact Crater Database

To date there are over 180 impact structures throughout the world, we invite you to explore them all with the impact crater database and interactive map. Search and read various details of the numerous impact structure found throughout the world.

www.impactearth.com
Impact-generated hydrothermal systems

Impact-processed crystalline rocks

Impact-generated glasses

Impact-generated crater lakes
Impact-generated hydrothermal systems

The hydrothermal system at Haughton

Intra-melt rock mineralization
Intra-melt rock mineralization
Veins within the central uplift
Fossil hydrothermal vents in the crater rim
Ries hydrothermal system

From Sapers, Osinski et al. (2017) MAPS.
Cross section of crater. Then have another, cold section with other habitats…


Impact-generated hydrothermal systems

Central Uplift

~5 to 150 km depending on size of projectile (Earth)
~10 to 250 km depending on size of projectile (Mars)

Ejecta (impact melt rocks and/or impact breccias)
Crater-fill deposits (impact melt rocks and/or impact breccias)

Impact-generated habitats for life

- Impact-generated hydrothermal systems
- Impact-processed crystalline rocks
- Impact-generated glasses
- Impact-generated crater lakes
Impact processing of target materials has created novel habitats.

Colonization of shocked gneisses by **endolithic** microorganisms (Chroococcidiopsis-like cyanobacteria).

Cowan PNAS 2009;106:47:19749-19750
Impact processing of target materials has created novel habitats.

Colonization of shocked gneisses by endolithic microorganisms (Chroococcidiopsis-like cyanobacteria).

Impact processing of target materials has created novel habitats. Colonization of shocked gneisses by endolithic microorganisms (Chroococcidiopsis-like cyanobacteria).

- **Increased** porosity and translucence:
  - Greater penetration of light at the chlorophyll absorption maximum
  - Reduced effective optical thickness
- Provides a moist, UV-shielded and (relatively speaking) warm habitat.

Biomass levels in shocked gneiss


![Graph showing biomass levels vs. shock level with an R² value of 0.9765.](image-url)
Impact-generated habitats for life

- Impact-generated hydrothermal systems
- Impact-processed crystalline rocks
- Impact-generated glasses
- Impact-generated crater lakes
• Enigmatic **tubular features** observed in impact glasses from the Ries structure, Germany.
• They are **not** quench crystallites.
• The tubular features may spiral, bifurcate, etc.
• Suggested that **biological activity** may have played a role in the formation of the tubular textures (cf., volcanic glasses; e.g., Banerjee et al. 2007).

Comparison to volcanic glasses

- Tubular alteration textures in natural glasses:
  - E-H: putative bioalteration in impact glass.

It has long been suggested that during the early history of the Earth, asteroids and comets may have been responsible for the delivery of intact organic molecules and volatiles (e.g., Chyba, 1990; Chyba and Sagan, 1992).

- Four main “impact” delivery mechanisms: interplanetary dust particles (IDPs), airbursts, cometary impacts, and meteorites.
- Studies of carbonaceous chondrites have shown that they contain:
  - >80 amino acids.
  - High amounts of CHONPS.
  - Ammonia, methane, acetylene, acetonitrile, hydrogen isocyanide, formic acid, isocyanic acid, cyanoacetylene, formamide, thioformaldehyde....
Several authors have suggested that chemical interactions between water and various minerals might have been important in enabling the origin of life.

Minerals may have played a role in both the formation of simple organic molecules such as formaldehyde and, possibly, in the formation of molecules as complex as RNA, through reactions mediated by clay minerals.

Ferris (2005, 2006): Montmorillonite is able to catalyze a variety of organic reactions, in particular the formation of RNA.
Hypothesis:

*Impact craters can generate conditions suitable for the emergence of life through the production of substrates for prebiotic chemistry, through delivery of life-essential elements, and through the production of habitats for microbial life.*
Thermobaric phase

Succession phase

Implications for Mars

Why the Martian subsurface?

>50% of the Martian geologic record
>3.5 Ga is preserved

surface no longer habitable

Mars

Noachian
end of magnetic field
significant loss of atm
oldest zircon

Hesperian
end of widespread surficial water

Amazonian
surface water no longer stable

Earth

Hadean
earliest geochemical evidence of life

Archean
earliest microfossil

Proterozoic

Phanerozoic

Oxygenic photosynthesis
Anoxygenic photosynthesis
Chemolithotrophic, Acetyl CoA CO₂ fixation

significant surficial biosphere
Jezero Crater, Mars
Hydrated silicates associated with impactites

Tornabene, Osinski et al. (2013)
Impact cratering is a geological process that is common to all planetary bodies in the solar system and, likely, the universe. Impact events can deliver the chemical ingredients for life (organics, etc). Impact craters can generate conditions suitable for the emergence of life, including:

- Substrates suitable for prebiotic chemistry (clays, pyrite, pumice, etc).
- Habitats for life (hydrothermal systems, crater lakes, etc).

Impact craters, once formed on Early Earth – and by analogy on other planets – would have represented prime sites that served as protected niches where life could have survived and evolved.
The Role of Meteorite Impacts in the Origin of Life

G.R. Osinski,1,2 C.S. Cockell,3 A. Pontefract,4 and H.M. Sapers5,6,*

Abstract

The conditions, timing, and setting for the origin of life on Earth and whether life exists elsewhere in our solar system beyond represent some of the most fundamental scientific questions of our time. Although the bombardment of planets and satellites by asteroids and comets has long been viewed as a destructive process that would have presented a barrier to the emergence of life and frustrated or extinguished life, we provide a comprehensive synthesis of data and observations on the beneficial role of impacts in a wide range of prebiotic and biological processes. In the context of previously proposed environments for the origin of life on Earth, we discuss how meteorite impacts can generate both subaerial and submarine hydrothermal vents, abundant hydrothermal–sedimentary settings, and impact analogues for volcanic pumice rafts and splash pools. Impact events can also deliver and/or generate many of the necessary chemical ingredients for life and catalytic substrates such as clays as well. The role that impact cratering plays in fracturing planetary crusts and its effects on deep subsurface habitats for life are also discussed. In summary, we propose that meteorite impact events are a fundamental geobiological process in planetary evolution that played an important role in the origin of life on Earth. We conclude with the recommendation that impact craters should be considered prime sites in the search for evidence of past life on Mars. Furthermore, unlike other geological processes such as volcanism or plate tectonics, impact cratering is ubiquitous on planetary bodies throughout the Universe and is independent of size, composition, and distance from the host star. Impact events thus provide a mechanism with the potential to generate habitable planets, moons, and asteroids throughout the Solar System and beyond. Key Words: Origin of life—Impact craters—Hadean environment—Hydrothermal systems—Crater lakes—Lithophytic habitats—Geobiology. Astrobiology 20, 1121–1149.

1. Introduction

When and where life originated on Earth and whether there existed, or exists, life elsewhere in our solar system represent some of the biggest unanswered scientific questions of our time. These questions provide motivation for the near-term robotic exploration of Mars, including the return of samples, as well as the exploration of more distant targets, both within (e.g., Europa and Enceladus) and outside our solar system. But how did life on Earth begin? There is some consensus regarding the requisite conditions for the transition from prebiotic chemistry to living systems: a maintained excess of Gibbs free energy (∆G), a solvent (water), a mode for the encapsulation and concentration of prebiotic molecules, a mechanism of information storage, and the presence of catalytic molecules such as enzymes (e.g., Pace, 2001; Monnard and Deamer, 2002). Although there is widespread speculation on the geological setting for the origin of life, the earliest geological and biological evidence for early life and the putative conditions on the early Archean or Hadean Earth provide some environmental constraints. Several theories suggest a hot, aqueous environment for the origin of life (e.g., Pace, 1991; Stetter, 2005), and submarine hydrothermal vents have been widely proposed as candidate environments for prebiotic chemistry (e.g., Orgel, 1998; Nisbet and Sleep, 2001; Copley et al., 2007; Martin et al., 2008; Russell et al., 2013). Indeed, while still debated, many phylogenetic tree reconstructions when using molecular analyses of 16S rRNA combined with metabolic studies suggest a hyperthermophilic last universal common ancestor.

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Questions?

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