Opinion
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The evolutionary and ecological benefits of asteroid and comet impacts

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Commonly viewed solely as agents of destruction, asteroid and comet impact events can also have a beneficial influence on processes from the molecular to the evolutionary scale. On the heavily bombarded early Earth, impacts might have delivered and caused the synthesis of prebiotic compounds that eventually led to life. At the organismal and ecosystem level, impact events can provide new habitats through the shock processing of target materials and by enhancing water availability, such as within intracrater lakes. At the evolutionary level, by destroying entire groups of organisms, impacts might have been instrumental in enabling the rise of new groups, such as the dinosaurs and mammals. Here, we synthesize the emerging literature on the beneficial effects of impacts to provide a novel perspective on these extraterrestrial agents of biological change.

Impacts as a source of energy

There are now >160 asteroid and comet impact craters that have been identified on the surface of the Earth. These craters represent a small subset of the total impacts that have occurred during the history of life. Scaling to the square of the velocity, which is $\sim$17–18 km^{-1} for an asteroid and 40–50 km^{-1} for a comet, the kinetic energy associated with these events is enormous. The collision of a 10-km-diameter rock can release the equivalent energy of 10 million megatons of TNT [1], 1000 million times greater than the atomic bombs dropped on Hiroshima during the Second World War. An event on such a scale is expected to occur on average once every 100 million years, and to cause global-scale extinctions. It is a rock of this size that might have been involved in the Cretaceous–Tertiary (K/T) extinction 65 million years ago (MYA) [2,3]. It is perhaps not surprising, therefore, that the biological destructiveness of impact energies has significantly influenced our view of these objects and their role in ecological and evolutionary processes. Although it is true that impact events are biologically destructive, recent literature has revealed that the energy they release can also be beneficial at the molecular through to the evolutionary scale (Figure 1). The term 'beneficial' might be construed to be subjective and teleological. When we speak of 'beneficial effect' in this article, we mean any process that improves the conditions for the origin and evolution of life or that expands the available habitat for a given organism. Here, we provide a synthetic overview of the beneficial effects of impacts.

Benefits at the molecular level

The organic compounds that gave rise to life could have been formed by many processes, such as electrical discharges or UV radiation in the atmosphere of the Earth. However, calculations suggest that impact events were just as important as these other sources [4]. Asteroid and comets would have been beneficial for prebiotic syntheses leading to the molecules required for life by: (i) directly delivering the organics necessary for prebiotic reactions that eventually led to life; and (ii) providing the energy for the formation of organic polymers and other complex molecules that are necessary for life, such as nucleotides (e.g. [5,6]).

One estimate of the quantity of organics that might have been delivered by asteroid and comet impacts to the early Earth (3.8 billion years ago and before) gives a figure of 3.6×10^4 kg y^{-1} [4]. Although the presence of organics has been directly observed on comets [7], the organic inventory of comets is not well known; however, meteorites recovered on Earth suggest that a diverse suite of compounds could have been delivered to early Earth by

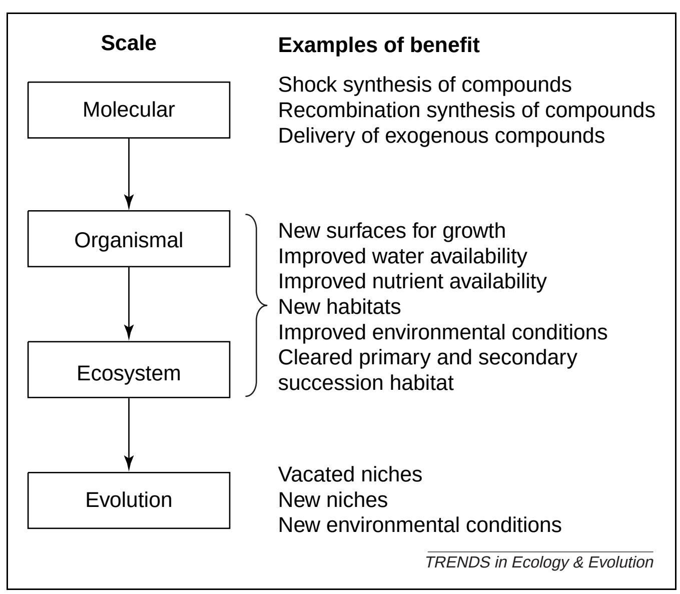

Figure 1. Examples of the benefits of asteroid and comet impacts events from the molecular to evolutionary level.

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impacts [8–11]. More than 100 different organic species have been recovered from meteorites, including polycyclic aromatic hydrocarbons and, perhaps more significantly, amino acids, the building blocks of proteins [9].

Impact events generate shock waves, which provide energy for organic syntheses, quite apart from the direct delivery of the organics themselves. Several reports on shock synthesis of organic compounds have now been published. For example, Fegley *et al.* estimated that, through the process of shock heating and rapid quenching, between 3×10^{11} and 14×10^{11} molecules of HCN could have been rained out into the oceans every year on the early Earth [12]. HCN can rapidly polymerize and act as the precursor for a range of important prebiotic materials, including amino acids. Experiments involving the simulated shock of solid benzene at 77K have yielded alkanes, alkenes and aromatic hydrocarbons with molecular weights of up to 306 [13], some of which have also been detected in meteoritic material [8]. These experiments reveal how organics might have been formed either in the early Solar System, eventually to be delivered to Earth, or on the Earth itself.

Similarly, the recombination of shock-vapourized gases during impact might have contributed organic material. Simulations of shock vapourization of terrestrial rocks and meteoritic material using lasers resulted in a variety of different products, including HCN [14]. Laboratory simulations using a high-powered laser and a methane-rich mixture resulted in the production of HCN and acetylene [15]. Laboratory simulations suggest that organic compounds are formed in the impact plume as the extra-terrestrial object enters the atmosphere of the Earth, further contributing to the inventory of compounds available for prebiotic chemistry [16].

Finally, early impactors might have delivered a significant percentage of the water contained within the oceans. If just 10% of the inventory of impactors on early Earth were icy comets (the rest being asteroids), this would have been sufficient to deliver the total mass of water present on Earth today [17,18], although the relative importance of the different types of impactor responsible for delivering this water is still uncertain. Thus, as well as making a substantial contribution to the delivery and synthesis of the precursors from which life would be eventually be assembled, impact events delivered the solvent that would eventually be required for life to carry out biochemical reactions in the first place.

Benefits at the organismal and ecosystem level

The impact of an asteroid or comet with the surface of the Earth has two profound effects that are relevant for surface-dwelling life. First, the impact delivers a source of energy and, second, it rearranges the hydrological cycle, with implications for the availability of liquid water, which is essential for life.

As three-quarters of the Earth is ocean, most impacts occur in water and one initial effect is the large-scale movement of bodies of water. Investigations of strata in a corehole 30 km northeast of the Mjølnir crater, formed in the late Jurassic by the impact of an object with the 300–400-m deep palaeo-Barents Sea, suggests that the impact event mixed water masses and caused a large introduction of nutrients into the Sea [19]. High concentrations of marine algae suggest that the increase in the availability of ammonia, nitrates, phosphates and iron was responsible for the post-impact nutrient bloom. The backwash of a tsunami, caused by the impact, is postulated to be the reason for the high concentrations of freshwater algae in the strata. These algae would have been washed in from regions outside the crater.

What about impacts on land? During impact, target rocks are heated to temperatures in excess of 800K and are shocked by the pressure wave, the extremity of these effects being directly related to the scale of the impact [20]. Water heated by the impact causes the formation of hydrothermal systems, which have been documented in several craters on Earth on the basis of high temperature mineral alteration [21–23]* and they might, in the early stages following impact, have provided a source of hot water for thermophilic and hyperthermophilic microorganisms (Figure 2). Impacts in oceans and shallow continental shelf areas also generate hydrothermal systems if they make contact with rocks. The intense heat and pressure of impact will sterilize the ground in its immediate area, resulting in the formation of an extreme primary succession habitat that is then available for new colonization. This situation is analogous to newly formed volcanic terrains. Further from the crater, the disturbance of existing ecosystems by the blast wave will cause the formation of secondary succession habitat in vegetated biomes, which might itself offer benefits to species that can take advantage of disturbed vegetation [24].

Long before the crater has cooled down, the excavation cavity formed in the ground will collect water and, within these intracrater ponds or lakes (Table 1), lacustrine ecosystems become established, depending upon the size of the structure. Even today, many impact craters still support such lakes (Figure 3). The biota associated with impact crater lakes has now been studied in several cases. The low biomass and poor diversity of the 3.4-km-diameter New Quebec Crater in Canada and the 18-km-diameter El'gygytgyn crater in Siberia [25,26] contrasts with the rich, abundant bacterial and algal ecosystem associated with the 1-km-diameter Tswaing impact crater

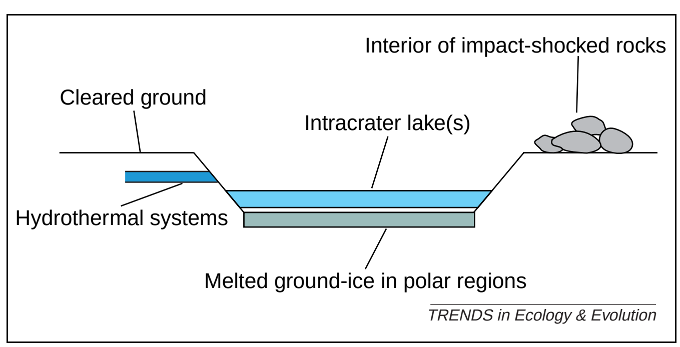

Figure 2. Examples of habitats formed inside and around an impact crater.

* Kring, D.A. *et al.* (2003) Impact lithologies and post-impact hydrothermal alteration exposed by the Chicxulub scientific drilling project, Yaxcopoil, Mexico (abstract) Third International Conference on Large Meteorite Impacts, August 2003, Nördlingen, Germany.

Table 1. Examples of land-based impact craters that contain lakes

Name of crater	Country	Size of crater (km)	Age of crater (million years)
Bosumtwi	Ghana	10.5	1.03 ± 0.02
Brent	Canada	3.8	450 ± 30
Clearwater	Quebec, Canada	26	290 ± 20
El'gygytgyn	Russia	18	3.5 ± 0.5
Lonar	India	1.83	0.052 ± 0.006
New Quebec	Quebec, Canada	3.44	1.4 ± 0.1
Tswaing	South Africa	1.13	0.22 ± 0.05

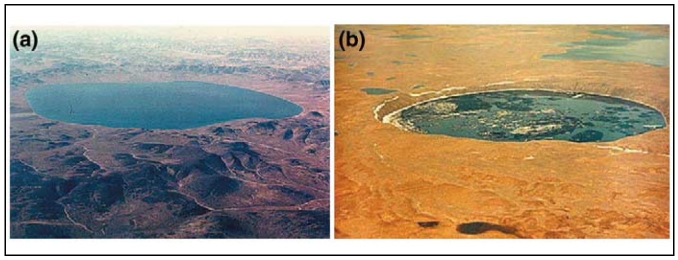

Figure 3. Examples of intracrater lakes. **(a)** El'gygytgyn in Siberia and **(b)** New Quebec in Canada.

in South Africa [27–29]. The Tswaing crater is situated in South African bushveld and receives organic input from the rich vegetation that grows within the impact crater cavity, whereas the New Quebec and El'gygytgyn craters are associated with extreme polar environments, where annual temperatures are low and water bodies remain nutrient poor. Although the biota that takes advantage of an intracrater lake will depend on the local climatic conditions, these examples show how impact excavation provides benefits for life by forming a cavity in which water collects.

Lakes are not specific to impact craters in the sense that any topographical low can harbour lakes. The low frequency of impact events (Box 1) makes their contribution to the formation of lakes insignificant compared with other processes, but nevertheless the lakes are still an advantageous side effect of otherwise ecologically destructive events.

A benefit that is linked more specifically to the processes of impact shock alteration is the formation of new habitats caused by shock processing of the target materials. The process of impact heating and shock can increase the porosity of rocks, thereby improving accessibility for microorganisms [30,31]. In some cases, light transmission is also increased, making shocked rocks more amenable to colonization by photosynthetic microorganisms [30]. These effects are caused by effects such as the fracturing of rocks and volatilization of minerals[†].

Benefits at the evolutionary level

Impact events with energies greater than a million megatons are believed to be able to cause atmospheric alterations on a global scale that are sufficient to cause widespread biotic extinctions; however, the role of impact events in causing extinctions remains controversial. Although many of the effects suggested for large body impacts would be detrimental to life (e.g. acid rain, darkened skies, fire ignition, and so on), these large-scale biotic extinctions would also be 'beneficial' for the groups that follow them in that niches are created or vacated into which organisms are able to radiate.

Levels of iridium, an element that is more abundant cosmically than in the crust of the Earth, were found to be elevated between 20 and 160 times above background at the K/T boundary [2]. The iridium anomaly has been suggested to be evidence for an involvement of an impact event in the eradication of ~75% of species, including most of the dinosaurs, 65 million years ago. The favoured scenario is that dust, soot and sulfates would have been lofted into the atmosphere and would have cut out sunlight, causing a shutdown of photosynthesis for over two years. However, following the K/T extinctions, the end of dinosaur groups, which until then had dominated land and ocean ecosystems, enabled the radiation of mammal groups.

Further back in time, the rise of dinosaurs, following the Triassic–Jurassic boundary 200 MYA, has also been linked to an iridium anomaly [32]. With an average concentration of 141 parts per trillion at the boundary, some seven times higher than the background levels, this too has been interpreted as a cosmic contribution from an impact. Shocked quartz, which is also diagnostic of an impact event, has been observed at the boundary in Italy and major perturbations in the carbon cycle are suggested from isotopic studies. A fern spike is also observed following the boundary, similarly to that seen after the K/T event, suggesting a rapid spread of fern taxa following the period of disruption. These hardy taxa would have been suited to recolonizing disrupted ecosystems. The effect of the impact is postulated to have led to 'ecological release', opening new niches for the survivors to radiate and spread globally [32]. The survivors that took advantage of these new niches were the dinosaur (theropod) groups that dominated for the next 135 MY.

Box 1. The frequency of impacts

The population of existing craters on Earth can be used to derive estimates of how frequently impacts occur. Craters >20 km in diameter are thought to be formed every 350 ka [42], 435 ka [43], 560 ka [44], or 740 ka [45]. Hughes finds craters >50 km in diameter are formed every 3.5 Ma, and those >100 km in diameter every 17 Ma [45]. Grieve and Shoemaker find craters >50 km in diameter form every 1.8 Ma, those >100 km are formed every 6.3 Ma, and those >200 km every 22 Ma [42].

Bland and Artemieva have produced a complete size-frequency distribution for terrestrial impacts, compiling data from a variety of sources, including the terrestrial crater record and Near-Earth Object estimates [46,47]. They find craters >20 km are formed every 0.58 Ma, craters >50 km every 2.9 Ma, those >100 km every 13.5 Ma, and those >200 km every 80 Ma. The current impact flux is thought to have been quite constant for the past 3 billion years [42,48]. Before this time, it was much higher. Hartmann *et al.* estimate that, 4.55 Ga ago, the impact flux was ~10^9 times the present value, declining to ~10^7 times by 4.49 billion years ago, and 10^3 times by 4.2 billion years ago [49,50]. Put another way, at 4.2 billion years ago, craters >200 km in diameter would occur every 80 000 years.

† Cockell, C.S. (2003) Beneficial microbial effects of impact events (abstract) 10th ESF Workshop, 'Biological Processes Associated with Impact Events', 29 March–1 April, 2003, Cambridge, UK.

As well as periodic effects on the course of evolution, it has been argued that the putative collision of a giant object with the Earth in its early history, which led to the formation of the moon, was necessary to make the Earth habitable in the first place. The removal of the first deep atmosphere and the alteration of the tilt of the Earth have been suggested as possible consequences of such an impact that led to an environment that was conducive to the evolution of the biosphere [33].

Astrobiological speculations

Impact events are a universal phenomenon and so the processes reviewed here could be relevant to other planets. Impact events might provide a source of heat, for instance, on the Saturnian moon, Titan [34]. Its cold reducing atmosphere provides limited opportunities for complex organic compounds to form, but, on the surface, in ephemerally heated environments, such as impact melt-sheets, organic syntheses could occur for periods of several thousand years[‡]. Thus, Titan can be viewed as a potential laboratory for understanding the principles of prebiotic processes that have been proposed for early Earth.

As impact events can create a local source of heat to melt ice, they might also be important on cold rocky planets as a means to generate transient water for prebiotic syntheses, or perhaps even liquid water for life. The subsurface of Mars, for instance, contains ground-ice, particularly at high latitudes [35]. The impact heating of this ice would generate hydrothermal systems conducive to supporting life, if it is present. Impact crater hydrothermal systems, although liable to be more short-lived than geothermal hotspots, could nonetheless provide environments with enhanced potential for microbial life. Such systems have therefore been suggested as high priority sites for the search for life on Mars [36–39]. The apparently equable conditions for life on Mars have led to the suggestion that impact events might have enabled the transfer of life between the terrestrial planets [40] (Box 2).

Experiments involving the impact of small projectiles into icy targets show that the energy from impact results in the formation of complex organics. These complex materials, generically referred to as 'tholins', are proposed as an explanation for the dark patches observed around impact craters on Europa, the ice-encrusted moon of Jupiter [41]. As these organics might eventually leach from the ice into the Europan ocean beneath, they might have significance not only for surface processes, but also for Europan ocean chemistry.

Because we know of no planetary system-forming process that is completely free of remnant material, impact events are likely to be a universal process on extrasolar rocky planets. From an ecological and evolutionary perspective, this somewhat trite observation is actually profound because it suggests that impact craters are the only habitat that we can speculate about with certainty on other planets. Not all planets necessarily exhibit volcanism, glaciation, lakes or other habitats familiar to us on Earth, but all rocky planets will have impact craters, even if submerged under a planetary-scale ocean. Thus, we can speculate that, on other planets, the energetic effects of impact events at least offer potential benefits for prebiotic syntheses and for the emergence and radiation of life, even if these benefits have yet to be realized.

‡ Thompson, W.R. and Sagan, C. (1992) Organic chemistry on Titan – Surface interactions. In Proceedings of the ESA Symposium on Titan SP-338, September 1991, Toulouse, France.

Box 2. Microbial survival after large impacts

It has long been thought that large impacts on the early Earth sterilized the planet, vaporising the oceans. Although life could have emerged several times, it was thought that viable populations could have only been maintained once the impact of large bodies had ceased after the end of the late heavy bombardment 3.9–3.8 billion years ago. The principal danger to early life was from re-entering impact-ejected material, causing a thermal pulse that was sufficient to boil the oceans [51]. However, it might have been thousands or millions of years before some of the material ejected into space from a large impact re-entered the atmosphere of the Earth and impacted the surface again. Therefore, it seems possible that some material from an impact large enough to sterilize the Earth could eventually re-seed the planet once conditions were equitable. This hypothesis was discussed by Wells *et al.*, who concluded that it is indeed viable [52]. Thus, one beneficial effect of large impacts might be to launch life into the refugium of space, enabling it to survive the environmental perturbation on Earth caused by the original impact. Of course, such life would then have to survive re-entering the atmosphere of Earth and another impact.

Summary

The energy released during the collision of an asteroid or comet with the Earth is sufficient to cause detrimental biological perturbations from the micro- to biosphere scale. Because impact events could also threaten human populations, it seems counterintuitive to regard these events as beneficial. However, the energies released during the impact can drive processes that are beneficial to life. The formation of biologically useful bonds at the molecular level, the shock alteration of rocks that makes them better habitats for microorganisms, the improved availability of biologically important nutrients and the clearance of whole ecosystems that enables new species to evolve and radiate are some of the beneficial examples. Future research will no doubt reveal more of these beneficial links between otherwise destructive impact energies and life. These processes require us to take a different view of the biological importance of asteroid and comet impact events, one that recognizes their contribution to the emergence, proliferation and evolution of life on Earth.

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