Impact cratering has affected the geologic and biologic evolution of Earth, from the earliest stages of accretion to the present. The environmental consequences of impact cratering and their biologic repercussions are illustrated by the Chicxulub impact event and its link to the Cretaceous-Tertiary (K-T) mass extinction event. While smaller impact events are more common, there were probably four to five additional impact events of this size during the Phanerozoic. These types of large impact events, and even larger ones, occurred more frequently earlier in Earth history. A particularly intense period of bombardment appears to have occurred ~3.8–3.9 Ga, corresponding to the earliest isotopic traces of life on Earth. These impact events may have made it difficult for preexisting life to survive or may have provided the necessary environmental crucibles for prebiotic chemistry and its evolution into life.

ABSTRACT

Impact cratering has affected the geologic and biologic evolution of Earth, from the earliest stages of accretion to the present. The environmental consequences of impact cratering and their biologic repercussions are illustrated by the Chicxulub impact event and its link to the Cretaceous-Tertiary (K-T) mass extinction event. While smaller impact events are more common, there were probably four to five additional impact events of this size during the Phanerozoic. These types of large impact events, and even larger ones, occurred more frequently earlier in Earth history. A particularly intense period of bombardment appears to have occurred ~3.8–3.9 Ga, corresponding to the earliest isotopic traces of life on Earth. These impact events may have made it difficult for preexisting life to survive or may have provided the necessary environmental crucibles for prebiotic chemistry and its evolution into life.

INTRODUCTION

It has become increasingly clear that impact cratering has affected both the geologic and biologic evolution of our planet. Although this view has its roots in the Apollo era (Fig. 1; McLaren, 1970), it was not widely recognized until studies linked the mass extinction that defines the end of the Mesozoic Era with the Chicxulub impact event (L.W. Alvarez et al., 1980; Hildebrand et al., 1991). That particular event also illustrates how a process that destroys some organisms can create opportunities for other organisms—in this case leading to distinctly different ecosystems during the Cenozoic Era. This dual pattern of disaster and opportunity has existed with impact events throughout Earth history, even during the earliest development of life.

The biologic consequences of impact cratering depend on many factors, including the energy of the impact event, the type of target materials, the type of projectile, and the ambient conditions on Earth at the time of impact. Consequences can range from the death of individual organisms to the complete extinction of species. While the former can be the direct result of an impact event (e.g., shock wave-induced hemorrhaging and edema in an animal’s lungs [Kring, 1997]), the more important biological effect, including extinction, will be through impact-generated environmental changes. To be an effective extinction mechanism, the environmental changes need to extend throughout a habitat range and exceed an organism’s ability to adapt (Newell, 1962). When the environmental effect is largely regional, the changes must overwhelm the migratory capacity of a species or last longer than its dormant capacity. When the effect transcends geographical boundaries and becomes global, the change must be rapid relative to the time scale of evolutionary adaptation or, again, last longer than the dormant capacity of a species. The minimum types of impact events needed to exceed these extinction thresholds.
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oldrs are not yet known. However, many of the environmental effects that could lead to extinction, particularly in the case of the Chicxulub impact event at the K-T boundary, have been identified.

THE CHICXULUB IMPACT EVENT Regional Effects

The Chicxulub impact occurred on a shallow carbonate shelf that is now part of the Yucatán Peninsula (Hildebrand et al., 1991). In the immediate vicinity of the crater, the shock wave, air blast, and heat produced by the impact explosion killed many plants and animals. The air blast, for example, flattened any forests within a 1,000–2,000 km diameter region (Emiliani et al., 1981), which would have included the highlands of Chiapas, central Mexico, and the Gulf states of the United States. Tsunamis also radiated across the Gulf of Mexico basin, producing reworked or unusually high energy sediments along the latest Cretaceous coastline (e.g., Smit and Romein, 1985; Bourgeois et al., 1988; Matsui et al., 1999) and up seafloor sediments down to depths of 500 m (Smit, 1999). The backwash of these waves was tremendous, depositing forest debris in 400–500 m of water (Smit et al., 1992). The abyssal portion of the Gulf of Mexico basin (W. Alvarez et al., 1992), the neighboring proto-Caribbean (Hildebrand and Boynton, 1990), and Atlantic Ocean (Klaus
et al., 2000) were also affected by the splashdown of impact ejecta, density currents, and seismically induced slumping of coastal margins (e.g., Smit et al., 1992) following magnitude 10 earthquakes (Kring, 1993). Within a few hundred kilometers of the Chicxulub crater, the thick blanket of ejecta was sufficient to exterminate life.

**Global Effects**

While these effects devastated organisms in the Gulf of Mexico region, the most significant environmental perturbations were the direct and indirect result of ejected debris that rained through the atmosphere, as first postulated by L.W. Alvarez et al. (1980). This material was carried in a vapor-rich plume that rose through the atmosphere into space. Once above the atmosphere, it expanded on ballistic trajectories, enveloping the whole Earth as it fell back into the atmosphere. The impact ejecta was distributed globally in a pattern much different from that of volcanic plumes, which simply rise into the stratosphere and then spread into latitudinal bands. Calculations indicate that most of this material reaccreted to the top of the atmosphere over a three-day period (Dürda et al., 1997), where it then settled to the ground over a longer period of time, depending on grain size. If a substantial portion of this dust was submicron in size, model calculations suggest the dust may have made it too dark to see for one to six months and too dark for photosynthesis for two months to one year, seriously disrupting marine and continental food chains and decreasing continental surface temperatures (Toon et al., 1998; Yang and Ahrens, 1998; Kring, 1992; Pope et al., 1997; Pierazzo et al., 1998; Yang and Ahrens, 1998; Kring, 1999). The worst appears to have been the $S$ species, which enhanced stratospheric $S$

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Sulfate aerosols were converted to sulfuric acid rain, whose effects compounded those produced by nitric acid rain. Nitric acid rain was produced from nitrous oxides that were created when the atmosphere was shock-heated by the impact event (Lewis et al., 1982; Prinn and Fegley, 1987; Zahnle, 1990). Acid rain could have defoliated continental vegetation and even aquatic plants in shallow, inadequately buffered lakes or seas whose entire water columns became acidic. Asphyxiation of animals by nitrous oxides and toxic poisoning by metals acid-leached from the ground have also been suggested (Prinn and Fegley, 1987), possibly compounding the toxic effects of metals from the projectile (Erickson and Dickson, 1987; Pierazzo et al., 1998). The nitric acid production may have produced a pH of 3–4 in the upper 100 m, if maximum estimates are correct, but this also seems unlikely (D'Hondt et al., 1994).

Sulfate aerosols significantly reduced the amount of sunlight reaching Earth's surface and would have, thus, enhanced the effects of ejected dust particles and soot produced by fires (discussed later). Darkness and cooler temperatures produced by these particles were relatively short-term, lasting only a few years. On the other hand, there may have been a longer-term increase in temperatures because a large quantity of greenhouse gases were produced from vaporizing sediments (CO₂ and H₂O), the projectile (CO₂ and H₂O, depending on the type of asteroid or comet), shock heating of the atmosphere (N₂O), carbonates dissolved by acidic waters (CO₂), and wildfires (CO₂ and N₂O; discussed later). However, the magnitude of greenhouse warming is still uncertain.

In addition, ozone-depleting Cl and Br were produced from the projectile, target water, target sedimentary rocks, target basement rocks, and postimpact wildfires. The amount of Cl injected into the stratosphere is believed to be five orders of magnitude greater than that needed to destroy the modern ozone layer (Kringle, 1999). However, this issue illustrates the current uncertainty of postimpact atmospheric conditions. While ozone may have been consumed by reactions with Cl, Br, and NO, reactions with dust and smoke particles, and heating by reentering debris and accompanying thermal radiation and increased solar absorption, the effects may also have been mitigated by ice, which briefly enhances planetary albedo, dust and smoke, which absorb solar radiation, NO₃, which strongly absorbs part of the ultraviolet spectrum, and sulfate aerosols, which scatter solar radiation. At the moment, there is a good list of the perturbing elements injected into the atmosphere, but the complex microphysical and chemical reactions that occurred have not been modeled.

On the ground, however, it is clear there were postimpact fires. Charcoal and soot, which are produced when vegetation or fossil carbon are burned, have been found in K-T boundary sediments around the world (e.g., Tschudy et al., 1984; Wolbach et al., 1990). Theoretical calculations suggest these fires were ignited by intense thermal radiation produced by ejecta reentering the atmosphere on ballistic trajectories (Melosh et al., 1990). Fires consumed large quantities of latest Cretaceous vegetation, burned many animals, and robbed herbivores of their food. Fires would have produced several secondary effects too, absorbing sunlight, possibly inhibiting photosynthesis, lowering atmospheric temperatures, and producing organic pyrotoxins (Wolbach et al., 1990).

As this brief review illustrates, several impact-caused perturbations on the ground and in the atmosphere could have contributed to the K-T boundary extinctions (Figs. 2 and 3). However, it was likely the combination of primary and secondary effects that was so deleterious. Different parts of the global environment would have been perturbed over diverse time scales (e.g., days for reentering impact ejecta, months for dust in the stratosphere, and years for sulfate acid aerosols). The initial effects would be added to and amplified by secondary effects and the ensuing collateral damage. The biological consequence of the Chicxulub impact was the collapse of entire ecosystems; cascading effects destroyed the infrastructure of the biosphere (e.g., collapse of food chains, loss of habitat), compounding the initial direct environmental effects. Thus, while the physical effects of the impact event may have been relatively short-lived, the time needed to reestablish chemical gradients,
repair food chains, and rebuild integrated ecosystems was much greater.

The details of the biologic crisis and its recovery are difficult to tease from the geologic record, but some progress is being made. Impact cratering theory suggests the crisis was global and, indeed, marine bivalve extinction intensities are global without any latitudinal or geographic variations (Raup and Jablonski, 1993). In both marine and continental settings, organisms with dormant or resting states fared better through the crisis. For example, planktonic diatoms that produce resting spores specialized to persist in benthic or deep-pelagic environments of low- to no-light conditions, and, during periods of stress, had a high survival rate (Kitchell et al., 1988). It has also been suggested that the loss of primary productivity and the subsequent collapse of food chains had much less an effect on organisms that were detritus feeders or starvation resistant (Sheehan et al., 1996). The recovery of these survival species, however, did not represent the full recovery of the ecosystem with robust food chains and attendant biochemical gradients. For example, it appears that while marine production may have recovered relatively quickly (albeit with a completely different population of organisms), the flux of organics to the deep sea took approximately three million years to recover (D’Hondt et al., 1998).

Among plants in the western interior of North America, the record of survival and recovery is marked by a dramatic increase in the ratio of fern spore to angiosperm pollen (Orth et al., 1981; Tschudy et al., 1984). The pioneering behavior of the ferns after the impact-generated wildfires is similar to their behavior after forest fires today. In Canada, both ferns and angiosperm taxa behaved in an opportunistic fashion depending on the preimpact plant community, suggesting the vegetation recovered from local seeds and spore, rather than being repopulated from distant communities (Sweet and Braman, 1992). Gymnosperms were generally lost at the boundary, suggesting the swamp forest canopy was destroyed for several years (Sweet and Lerbekmo, 1999), even at sites ~4000 km from the impact.

LIFE’S ORIGINS

The Chicxulub event is an example of how impact cratering can affect life and is likely to be only one of five to six such events during the Phanerozoic (Kring, 1995). Impact cratering also had an important effect much earlier in Earth history when life was initially being established. A particularly intense period of bombardment appears to have occurred ~3.9 Ga, which almost completely reset the U-Pb system in lunar highland samples in the Apollo collection (Tera et al., 1974). The event also seems to have put an upper limit on the ages of surviving impact melts in the Apollo collection (Ryder, 1990; Dalymply and Ryder, 1993). While the concept of a cataclysm has been controversial (Baldwin, 1974; Hartmann, 1975), recent analyses of impact melts in lunar meteorites (Cohen et al., 2000), which represent a much larger fraction of the Moon, have the same age limit and support a planetwide impact cataclysm.

The initial stage of intense impact cratering on the Moon is known as the Nectarian Period (3.8–3.9 Ga), which began with Nectaris impact and ended with Imbrium impact (Wilhelms, 1987). This period is believed to have been ~200 Ma long (Tera et al., 1974; Wilhelms, 1987), during which time at least 1700 craters >20 km diameter were produced, including at least 12 impact basins far larger than Chicxulub (Fig. 4; Wilhelms, 1984, 1987). The number of impacts occurring on Earth would have been an order of magnitude larger, implying >10,000 large impact events. This was followed by the Early Imbian Epoch, which began with the Imbrium impact and ended with the Orientale impact, again roughly 3.8–3.9 Ga, producing additional basin-size craters on the order of 1000 km diameter. These large impact events also produced swarms of secondary craters with diameters >20 km (e.g., Wilhelms, 1987), which were also large enough to cause dramatic effects. Impact events of these sizes on Earth would have been large enough to have affected the environment and most likely any life that had arisen. The largest impact events probably produced immense quantities of ejecta, temporarily charged the atmosphere with silicate vapor, and boiled away large quantities of surface water (Sleep et al., 1989; Sleep and Zahnle, 1998).

Interestingly, the earliest isotopic evidence of life on Earth comes from this same period of time (e.g., Mojzsis and Harrison, 2000). In addition, ribosomal RNA analyses of the most deeply branching organisms suggest that life is rooted among thermophilic or hyperthermophilic forms. Commonly, this is interpreted to mean that life originated (or survived the impact bombardment in) volcanic hydrothermal systems. However, during the period of bombardment, impact-generated hydrothermal systems were possibly more abundant than volcanic ones. The heat source driving these systems is the central uplift and/or pools of impact melt. In the case of a Chicxulub-size event (among the smallest ~3.9 Ga), melt pools may have driven a hydrothermal system for 10^5 yr (Kring, 1995). The

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incursions, the hydrothermal systems were filled with freshwater lakes or marine hot springs, and geysers, similar to those systems probably vented subaquously, like those in volcanic crater lakes or deep-sea vents. In addition to providing a suitable environment for thermophilic and hyperthermophilic forms of life, it has been suggested that the impacting objects may have seeded the surface of Earth with amino acids and other important organic materials (e.g., Chyba, 1993; Pierazzo and Chyba, 1999).

**CONCLUSIONS**

Impact cratering is a very energetic geologic process that has the capability of disrupting or redirecting the biologic evolution of a planet. In the case of the Chicxulub impact event 65 Ma, a large number of regional and global environmental effects were generated that were likely the cause of the mass extinction that marks the K-T boundary. The potential for disrupting the environment was larger and more frequent earlier in Earth history, particularly ~3.9 Ga when life with thermophilic and hyperthermophilic characteristics evolved. This implies that life either originated in these impact-dominated conditions or possibly that these forms of life were the type best suited to survive this brief period of intense bombardment. In the latter case, life may have originated under different conditions (e.g., Komor et al., 1988; Pezner et al., 1992). Large regions within these systems should have had appropriate temperatures for thermophilic and hyperthermophilic organisms. When the craters were subaerially exposed, the hydrothermal systems probably vented subaquously, like those in volcanic crater lakes or deep-sea vents.

**Impact Events continued from p. 5**

dimensions of these systems can extend across the entire diameter of a crater and down to depths in excess of several kilometers (e.g., Komor et al., 1988; Pezner et al., 1992). Large regions within these systems should have had appropriate temperatures for thermophilic and hyperthermophilic organisms. When the craters were subaerially exposed, the hydrothermal systems probably vented subaquously, like those in volcanic crater lakes or deep-sea vents. In addition to providing a suitable environment for thermophilic and hyperthermophilic forms of life, it has been suggested that the impacting objects may have seeded the surface of Earth with amino acids and other important organic materials (e.g., Chyba, 1993; Pierazzo and Chyba, 1999).

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conditions in different environments and only found itself frustrated by impact cratering (Maier and Stevenson, 1988; Chyba, 1993) as it was by Chicxulub.

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