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INSIDE

Impact Events and Their Effect on the Origin, Evolution, and Distribution of Life

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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.

Figure 1. Earthrise over Smythii impact basin with Schubert impact crater on horizon. Views like this during Apollo missions made it clear that Earth is part of a planetary system rather than an isolated sphere, subject to the same bombardment that battered the surface of the Moon. (Apollo 11 AS11-44-6551)

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 thresh-

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Impact Events *continued from p. 1*

olds 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 1000–2000 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; Smit et al., 1992). Tsunamis were 100–300 m high as they crashed onto the gulf coast (Bourgeois et al., 1988; Matsui et al., 1999) and ripped 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

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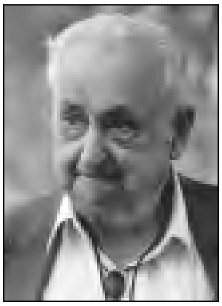

> "In the 1960 reorganization of the USGS Geologic Division, Linc became chief of the New England Branch. He and [wife] Esther moved to Melvin Village, New Hampshire, and weeknights Linc lived in his 'Penthouse' in the Back Bay in Boston. Randolph "Bill" Bromery was fascinated by and learned much from Linc in many discussions of the complex uranium-rich carbonates of the Cu-rich Shaba region of Zaire, including 'survival skills—using cognac for brushing our teeth, a unique and pleasant experience. Linc had very special humanity, and my life and career greatly benefited because our paths crossed.'"
>
> —Excerpted from Lincoln Ridler "Linc"Page (1910–1996), by James W. Skehan, *Memorials,* v. 30

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Notice of Council Meeting

Meetings of the GSA Council are open to Fellows, Members, and Associates of the Society, who may attend as observers, except during executive sessions. Only councilors, officers, and section representatives may speak to agenda items, except by invitation of the chair. Because of space and seating limitations, notification of attendance must be received by the Chief Executive Officer prior to the meeting.

The next meeting of the Council will be at 1 p.m., Monday, November 13, at the GSA Annual Meeting in Reno, Nevada.

CORRECTION: The fax numbers for registering for the 2000 GSA Annual Meeting in Reno are 303-443-1510 or 303-447-0648. An incorrect number was published on page 50 of the June issue of *GSA Today.*

GEOTRIP CANCELLATION: "Giant Steps Through Time," scheduled for September 16–October 1, 2000, has been cancelled.

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 (Durda 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., 1982; Covey et al., 1990).

In addition to the dust in the vapor-rich plume of ejecta, several important gas species were entrained. The Yucatán Peninsula, near the Chicxulub impact site, consists of carbonate and anhydrite deposits that overlie a crystalline silicate basement, so the impact produced several climatically active gas components, including aerosol-producing SO_2 and SO_3, greenhouse-warming CO_2 and H_2O, and ozone-depleting Cl and Br (e.g., Brett, 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

Impact Events *continued on p. 4*

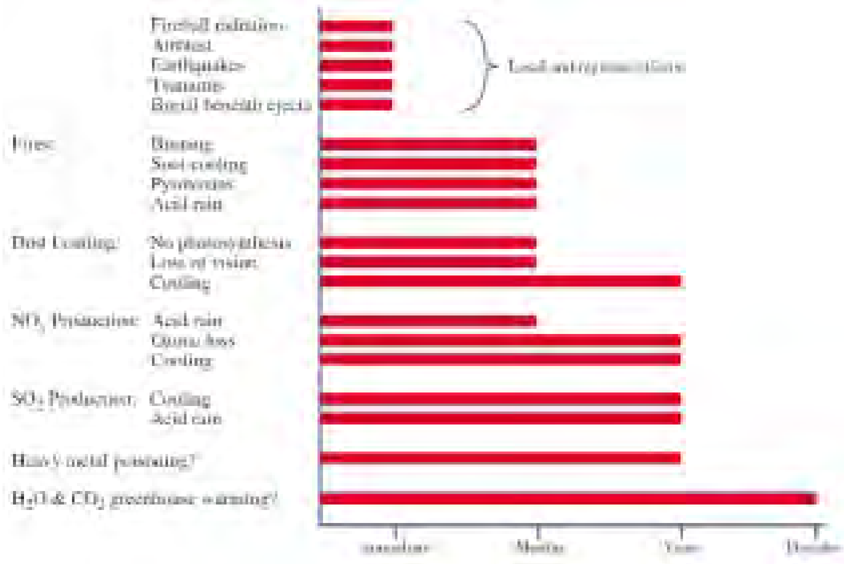


Figure 2. Relative time scales of several environmental perturbations caused by Chicxulub impact event.

Impact Events *continued from p. 3*

on the order of 10^5–10^6 times relative to modern abundances.

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). The amount of sulfuric acid was not, however, large enough to acidify oceans (D'Hondt et al., 1994; 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 (CO_2 and H_2O), the projectile (CO_2 and H_2O, depending on the type of asteroid or comet), shock heating of the atmosphere (N_2O), carbonates dissolved by acidic waters (CO_2), and wildfires (CO_2 and N_2O; 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 (Kring, 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, NO_2, 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,

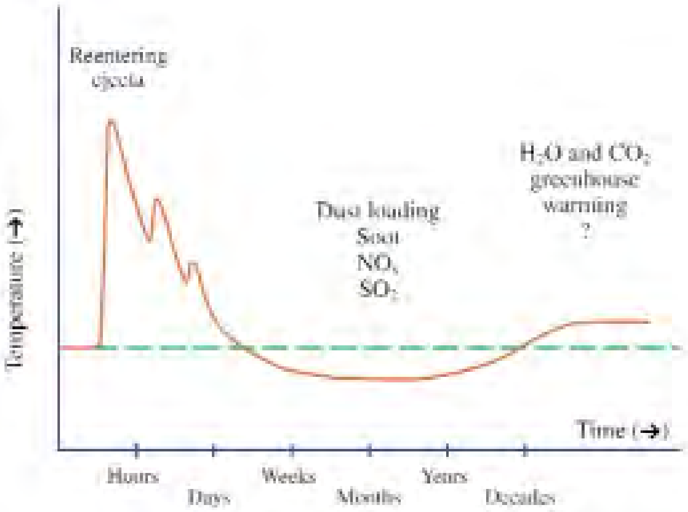


Figure 3. Thermal excursions produced by Chicxulub impact event as a function of time. Preimpact ambient temperature is marked with a dashed line.

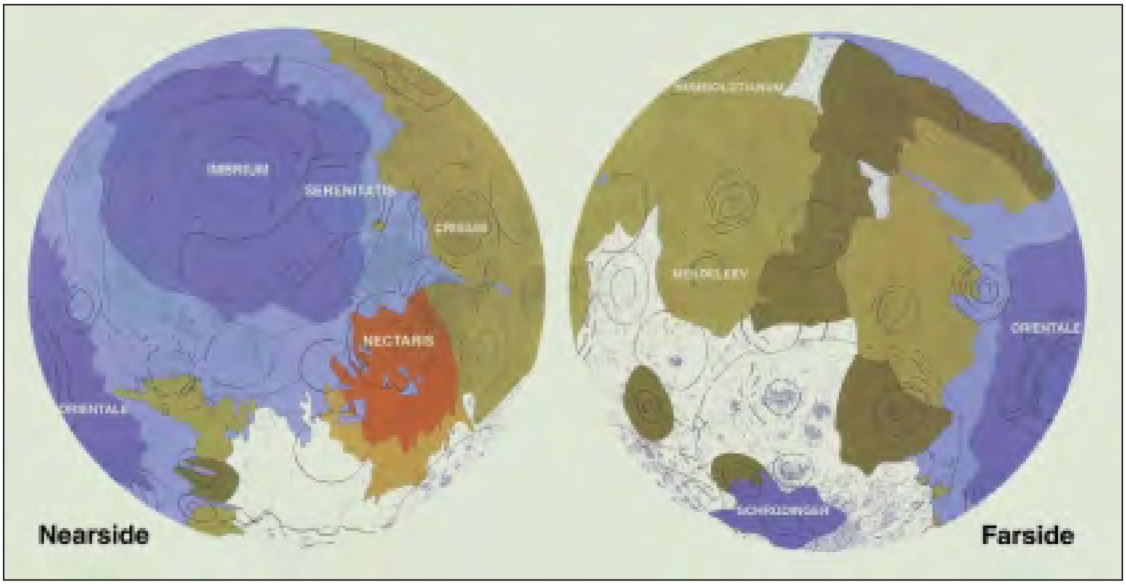


Figure 4. Maps showing regions of the Moon that were resurfaced during Nectarian Period (brown) and Imbrian Period (blue), and outlines of larger basins. Also shown are pre-Nectarian units (darkest brown) and areas of unclear stratigraphic relationships (gray) (Wilhelms, 1987).

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 faired 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., 1986). 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; Dalrymple 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.

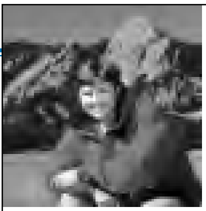
The initial stage of intense impact cratering on the Moon is known as the Nectarian Period (3.8–~3.9 Ga), which began with Nectaris impact and ended with Imbrium impact (Wilhelms, 1987). This period is believed to have been <200 Ma long (Tera et al., 1974; Wilhelms, 1987), during which time at least 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 Imbrian 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

Impact Events *continued on p. 6*

Dialogue

Sara Foland, CEO



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> “To learn geology one must travel widely and observe carefully, for geology is learned through the soles of your shoes, not the seat of your pants! The Earth is vast, its features, varied. One must climb mountains, travel over limitless plains, watch the waves of the sea beat unendingly upon the shore, study the work of mountain torrents as they carry their load to the sea, and learn to read the character of the rock record to understand the Earth. Delve deeply into the rocks, for truth is hidden there. Take heed to observe carefully the seemingly insignificant things, as each and every phenomenon and event is an integral part of nature’s process. Be untiring in your zeal to learn; and when you have accumulated facts, give careful thought to their interpretation. Let all your work be marked by ceaseless patience, tireless industry, vigilant caution, and prolonged study. Nature’s deeds are not erratic. What occurs is ruled by laws. When one is trained to read the geologic record, the deeds of nature become clear, usually simple, and amenable to understanding and description. The Earth gives no higher or nobler task than to study nature, to unlock her secrets and interpret her deeds.”
>
> *—Walter L. Manger et al.*
> *University of Arkansas Sigma Gamma Epsilon Initiation Ceremony*

Service at GSA: Support for Students

Jack May and Julie Williams May

Over the past several months, we’ve talked about GSA’s values of science and stewardship. This month, we’re ready to look at the third of our three Ss, which is service. One significant form of service GSA and its members perform is support for the professional growth and development of young geoscientists.

Exploring this topic with me are Jack May and Julie Williams May, both spring 2000 graduates of the University of Arkansas. Julie earned a B.A. in geology and a B.S. in earth science (cum laude); Jack received his M.S. in geology. They married in May and now live in Columbia, South Carolina, where Jack is pursuing a Ph.D. in geology and Julie a master’s degree in environmental resource management at the University of South Carolina.

Sara: I started out as a student member of GSA, and I remember how valuable that experience was for me. What stands out for you about membership in GSA?

Jack: We’ve been student members for the last three years, and GSA has provided us with lots of opportunities to interact with geologists in industry, academia, and government research. We attended the 1999 South-Central Section meeting in Lubbock, the 1999 annual meeting in Denver, and this past spring we helped host the South-Central Section meeting in Fayetteville.

Julie: Interacting at these meetings with professional members from so many different environments has helped us get a sense of “career.” It has helped with everything from making a commitment to the field of geology to developing interests in specific sub-disciplines and formulating career plans. All those exhibitors at meetings make gathering information easy, and travel grants help with the cost of getting there on a student budget.

Jack: The mentoring sessions have been particularly useful. I’ve talked one-on-one with people working for the U.S. Geological Survey, environmental consulting firms, and in the petroleum industry. I’ve asked what their jobs were like, what they’d do if they were just starting out, and whether continuing my education to the Ph.D. level is worthwhile. The sessions also covered practical matters like résumé writing.

Sara: In fact, GSA’s mentoring programs are intended to give you perspective and the skills you need in addition to your geoscience expertise. In funding these programs, I think Roy Shlemon was looking for a way to help young geoscientists begin making the transition from student to professional.

Jack: Certainly another growth experience for me came from presenting some of my research on sedimentation on the California continental borderland at a poster session in Denver last year.

Sara: Many of us had our first sweaty-palm experience presenting research at a GSA meeting. Section meetings are particularly good for this because you can present to peers and faculty from outside your home institution in a relatively small and somewhat informal venue. The great thing is that everyone wants you to succeed and people are extremely supportive. A related aspect of GSA’s support for students is our research grants program. Since the program began in 1933, GSA has awarded more than $7 million to 6,800 students.

Julie: Jack and I have certainly enjoyed and benefited from our participation in GSA, and we intend to be lifetime members. See you in Reno!

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; Pevzner 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 in mud pots, hot springs, and geysers, similar to those in volcanic terranes. When the craters were filled with freshwater lakes or marine incursions, the hydrothermal systems probably vented subaqueously, 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 in different environments and only found itself frustrated by impact cratering (Maher and Stevenson, 1988; Chyba, 1993) as it was by Chicxulub.

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