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Impact lethality and risks in today's world: Lessons for interpreting Earth history

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ABSTRACT

There is a modern-day hazard, threatening the existence of civilization, from impacts of comets and asteroids larger than ~1.5 km diameter. The average annual world fatality rate is similar to that due to significant accidents (e.g., airplane crashes) and natural disasters (e.g., floods), although impact events are *much* more rare and the deaths per impact event are *much* greater. (Smaller, more frequent impacts can cause regional catastrophes from tsunamis of unprecedented scale at intervals similar to the duration of recorded human history.) As the telescopic Spaceguard Survey census of Near Earth Asteroids advances, numerical simulations of the dynamic and collisional evolution of asteroids and comets have become robust, defining unambiguously past rates of impacts of larger, more dangerous cosmic bodies on Earth. What are very tiny risks for impacts during a human lifetime become certainties on geologic time scales. Widely reported errors in predictions of possible impacts during the next century have no bearing on the certainty that enormous impacts have happened in the past. The magnitudes and qualitative features of environmental consequences of impacts of objects of various sizes are increasingly well understood. Prime attributes of impacts, not duplicated by any other natural processes, are (1) extreme suddenness, providing little opportunity for escape and no chance for adaptation, (2) globally pervasive, and (3) unlimited potential (for Cretaceous-Tertiary [K-T] boundary-scale impacts and larger) for overwhelming destruction of the life-sustaining characteristics of the fragile ecosphere, notwithstanding the rather puny evidence for impacts in the geologic record. A civilization-ending impact would be an environmental and human catastrophe of unprecedented proportions. The K-T-scale impacts, of which there must have been at least several during the Phanerozoic (past 0.5 b.y.), are 1000 times more destructive. No other plausible, known natural (or human) processes can approach such catastrophic potential. The largest impacts must have caused mass extinctions in the fossil record; other natural processes could not have done so. Perspectives concerning both the potential modern-day destructive potential of impacts and conceivable, almost miraculous refugia in our own world provide a new gestalt for thinking about past cataclysms.

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INTRODUCTION

The idea that cosmic impacts on the Earth have played a significant, or even dominant, role in mass extinctions (and subsequent explosive radiation of new species) has evolved from widespread skepticism to substantial acceptance during the two decades since publication of the Alvarez et al. (1980a) hypothesis concerning the Cretaceous-Tertiary (K-T) boundary. However, there remain pockets of nonacceptance as well as a wide spectrum of opinions about the degree to which impacts have influenced evolution. Even among those who fully accept a role for impact in the K-T boundary extinctions, views range all the way from belief that the only substantiated case of an impact playing a role in mass extinction was the Chicxulub impact 65 Ma, which is viewed as just hastening the demise of already stressed populations, to the hypothesis of Raup (1991), that all mass extinctions, large and small, could have been caused by sudden environmental changes due to impacts.

As the Alvarez hypothesis was researched, awareness grew among scientists and the public of the modern-day risk to civilization from cosmic impacts. Once the purview of science fiction, it has become widely accepted (e.g., the report of an independent Task Force set up by the British Government; Atkinson, 2000) that the threat of a calamitous impact ranks among other hazards meriting national and international attention and consideration of preventative measures. While the chances of impact with an asteroid larger than 1.5 km diameter (deemed sufficient to threaten modern civilization; Chapman and Morrison, 1994) are very small, about one chance in several hundred thousand per year, the potential consequences are so enormous (perhaps the deaths of a quarter of the world's population) that the annualized fatality rate is similar to fatality rates associated with other natural hazards, such as floods and earthquakes (Fig. 1).

Research on the impact hazard, especially during the 1990s, has yielded a voluminous literature on the numbers and physical traits of the impactors, on the physical and environmental effects of impacts, and even on the potential response of human society to an imminent impact or to the aftermath of one. With the perspective from modern research on the impact hazard, the issues faced by historical geologists trying to understand the role of impacts during Earth history can be viewed from a new gestalt.

However, the modern-day impact hazard is not well understood by the public, by policy makers, and even by most scientists. Both the extremely low probabilities and the extremely great consequences of impact tax our intuition and common sense, because they are so far beyond the realm of our personal, or even historical, experience. Therefore, before applying insights from studies of the modern impact hazard to the historical record (the subject of a following section), I first introduce the impactor population and what is known about the consequences of impacts. I then discuss the issues of risk perception and uncertainties in impact prediction in order to demonstrate that they have no bearing on the certainty that impacts with unparalleled ecological consequences happened in the past. I then discuss the implications for the role of impacts in Earth history from lessons learned in the study of the impact hazard.

The following assertions about past mass extinctions are justified later herein.

It is virtually certain that several other impacts have occurred during the Phanerozoic (past 0.5 b.y.) that had at least the energy and potential ecological consequences of the Chicxulub K-T boundary impact, and that many other impacts have occurred with potential global consequences nearly as great. This is not a hypothesis: it is an inescapable fact derived from robust knowledge of asteroids and comets.

There is no other plausible, known kind of natural calamity that can possibly approach asteroid and/or comet impact in terms of the suddenness of the onset of devastating global consequences. (I exclude human devastations such as nuclear war, as well as other conceivable but unlikely disasters; e.g., a nearby supernova.) I assert that this suddenness, ranging from minutes to months, greatly magnifies the devastation compared with any other equally profound geologic, oceanic, or meteorological catastrophe.

The largest impacts during the Phanerozoic must have caused mass extinctions and, conversely, no other known plausible mechanism can approach the magnitude of consequences of such impacts. Therefore, the largest mass extinctions must have been caused by impact. (Only if required evidence of such impacts is missing from the geologic record must one then turn to the unlikely alternative explanations, e.g., a nearby supernova or explosion of an unexpectedly stupendous supervolcano.)

What is commonly accepted among impact hazard researchers as the threshold size of asteroid that could terminate civilization as we know it (1.5 km diameter) is more energetic than the explosive force of the world's combined arsenals of nuclear weapons by a factor of ~20. Yet the magnitude of the K-T boundary impactor (10–15 km diameter), and each of the several other equivalent or larger impacts that must have occurred since the Phanerozoic, is equivalent to a thousand civilization-ending impacts, all occurring simultaneously. The miracle is that anything survived. Perhaps the best way to visualize mass extinctions is to try to imagine the refugia that might exist for us, and for various species of animals and plants, in our modern world after it has been utterly devastated by an unimaginably colossal holocaust.

THE POPULATION OF IMPACTORS

Geologists have traditionally invoked the uniformitarian concept that continuous geologic processes observable today can account for what is observed in the geologic record of the past. In recent decades, a reasonable balance has been achieved between this two-century-old tradition and the important role

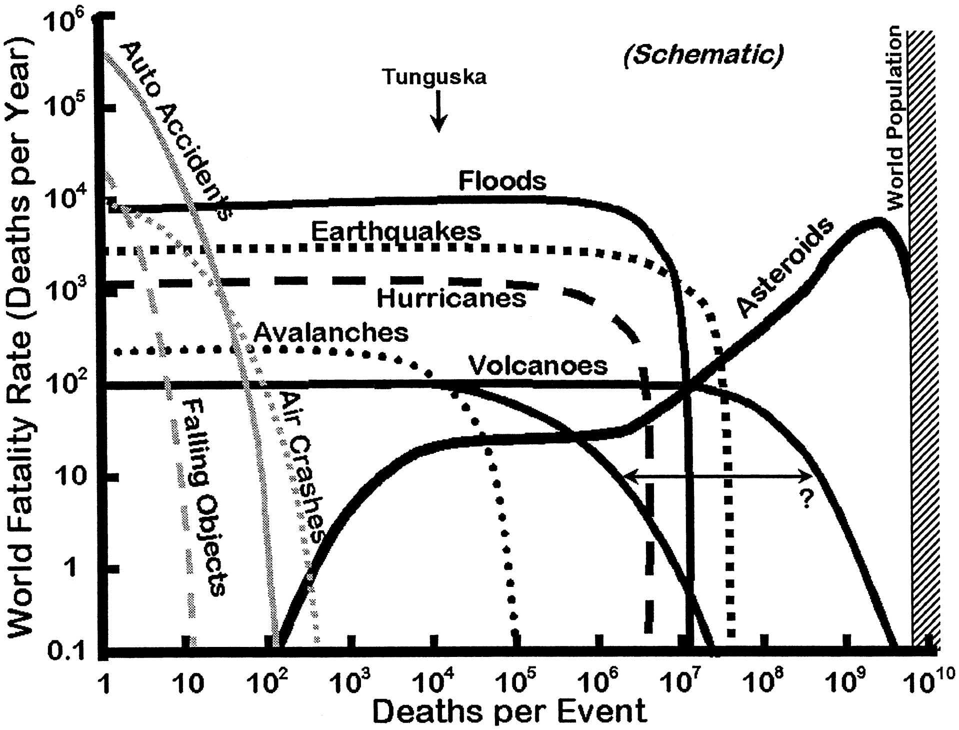

Figure 1. Schematic illustration of approximate average annual worldwide fatality rate for various kinds of accidents and natural disasters of various magnitudes. Accidents generally kill only a few people at one time, although accidents involving large transportation vehicles (e.g., aircraft) can kill hundreds. Natural disasters, as a class, are far less deadly than automobile accidents, but the largest among them can be far more deadly per event. Natural disasters comparable in lethality to Tunguska-class impacts (which occur every century or two; see downward pointing arrow) are about two orders of magnitude more frequent than such impacts. Most natural disasters have natural upper limits to lethality, because they are confined to particular geographic localities and/or are limited by physics or by strength of Earth's crustal materials in maximum magnitude. The upper limit in lethality of explosive volcanism is less well known; two alternative limiting curves are shown (see double-headed arrow), one extending roughly to consequences of impact of a 1–2-km-diameter asteroid. Only asteroids and comets have no upper bound in size and could, conceivably, eradicate the human species. In terms of fatality rate, asteroids dominate over all other natural disasters combined for individual events that kill more than 10^8 people at once, and are maximized for civilization-threatening impacts that can kill 10^9 people or more.

of episodic, even catastrophic, geologic processes. However, when geoscientists turn their attentions away from their specialties, old habits can reemerge. Frequently during this conference ("Catastrophic Events and Mass Extinctions: Impacts and Beyond"), speakers from geological and paleontological backgrounds made statements such as, "for this particular mass extinction, there is no reason to invoke an ad hoc impact from the heavens." They apparently miss the point, developed robustly over the past 70 yr, that cosmic impacts—despite their rare, catastrophic manifestations on Earth that concern us here—are part of an ongoing, continuous process that is observable today and has necessarily operated during the past history of the Earth.

Impact hazard researchers currently direct most attention to telescopic searches for Near Earth Asteroids (defined as those so-called Earth-crossing asteroids [including dead comets] whose orbits cross the Earth's orbit, in the sense that their closest and farthest distances from the Sun include 1 Astronomical Unit, the mean distance of the Earth from the Sun, plus the so-called Amors, which get as close to the Sun as 1.3 times the Earth's distance from the Sun). Depending on details of counting, currently more than 1550 are known, even though the first asteroid in an orbit that actually crosses the Earth's orbit was not found until 1932 and fewer than 20 Near Earth Asteroids were known as recently as the early 1970s. Currently, numerous telescopes equipped with modern detectors systematically scan the skies. Astronomers assemble data on detections and calculate orbits for these bodies. About one-half of all Earth approachers larger than 1 km diameter have been cataloged, as well as large numbers of smaller bodies ranging to the size of a small house.

These are just the largest, and potentially most dangerous, of a vast complex of interplanetary objects and particles in Earth-approaching orbits, ranging in size from enormous asteroids like Eros (34 km long; Veverka et al., 2000) and still larger comets, to rocks and dust particles. The basic physics of how this debris is created (by hypervelocity collisions among the debris) and how it is lost (by collision with the Sun or planets, and other loss mechanisms) has been understood for a long time. For example, the collisional cascade that creates and maintains the population of smaller bodies was explained by Piotrowski (1953) and Dohnanyi (1969); modern research has made changes that only specialists could care about. Fundamentally, the asteroids and smaller debris orbit around the solar system (inside of Jupiter's orbit) in a way that, despite some regularities, generates essentially random encounters and collisions among themselves at speeds of many kilometers per second. From the well-known mechanical properties of the common materials of which the debris is composed (rock, ice, carbonaceous mud, metal), the objects inevitably are broken by such collisions into smaller fragments and dust.

The resulting size distribution (numbers as a function of size) from multihundred kilometer asteroids and comets down to dust grains is well known and essentially invariant (cf. Durda et al., 1998). Dust grains are abundant and the Earth's large cross section continuously sweeps them up, as anyone can observe on a clear dark night: a meteor flashes through the upper atmosphere, as viewed from one location on the ground, every few minutes. Dust detectors on spacecraft confirm the widespread distribution of such grains throughout interplanetary space. Impacts of meter-sized bodies are much more rare, but are routinely observed by downward-looking satellites searching (primarily) for signs of military activity (Nemtchinov et al., 1997), and occasionally by ordinary human beings, as stunningly brilliant fireballs. For example, a 5-m-diameter impactor shone 10 times brighter than the Sun, as observed from the Yukon, when it struck in January 2000 (Brown et al. 2000), yielding some precious meteorite fragments.

Impactors several tens of meters and larger are too uncommon to strike regularly during a human lifetime, although the 15-Mt-equivalent Tunguska event in 1908 is well documented (probably caused by an asteroid ~50 m in diameter). However, objects of these sizes passing within a few million kilometers of the Earth and the Moon are regularly discovered by the telescopic scanning programs, especially by the Spacewatch Program on Kitt Peak, Arizona, which is optimized for discovering smaller bodies. The sampling becomes a complete census for Earth-approaching bodies larger than ~7 km diameter, not counting rare comets that can approach from the darkness of the outer solar system.

It is purely a matter of random chance, equivalent to rolling dice, when an impact will happen—whether a faint meteor streaking across the sky or a dinosaur-killing impact—but the average frequencies of impacts of objects of different sizes is well known and has not significantly changed since Shoemaker's (1983) review. Subtle regularities cause only slight departures from purely random chance. Specialists debate the exact numbers of bodies of specific sizes. However, differences are rarely greater than a factor of a few, and are often less than a factor of two. For example, it was long estimated that the number of Earth-approaching asteroids larger than 1 km diameter might be ~1500. During the last few years, there has been a well-publicized debate (e.g., Rabinowitz, 2000; Bottke et al., 2000; Stuart, 2001) about whether that number is really as low as 700 or as high as 1200. The answer has potentially important political consequences, such as whether NASA can reach its committed goal to find 90% of such objects by 2008 (Pilcher, 1998) without building more, larger search telescopes. Such arguments are inconsequential, however, in the context of impact catastrophes past or future.

Not only are the numbers and impact frequencies of interplanetary objects of all sizes well known today, but today's samplings and census are known to have been generally unchanged during the past 3.5 b.y. The physics of these bodies and their collisional evolution is well understood, and must have been as applicable in the past as today. Furthermore, understanding the sources and sinks of these bodies and their dynamics (e.g., how they move through the solar system on time scales ranging to billions of years) has developed remarkably in the past decade due to the advent of inexpensive, very fast computers. Although Kepler's Laws were never in doubt, the dynamic systematics of the entire complex of asteroids and comets has become well understood only during the past five years. Furthermore, examination of the cratering record on the Earth and terrestrial planets—and especially on the Moon—has demonstrated the continuity through the past 3.5 b.y. of impact processes. Specialists are interested in minor variations in impact rates and in the shape of the size distribution. However, since the late heavy bombardment ended ca. 3.8 Ga, the impact rates at all sizes have never varied by more than factors of a few, except (probably) for brief, transient showers of modest magnitude that have made a negligible contribution to the cumulative record of craters.

Table 1 translates the known, largely invariant size distribution of interplanetary projectiles, and their rates of colliding with Earth, into some relevant chances of impact by bodies of three interesting sizes: a small asteroid 200 m across capable of creating a devastating tsunami unprecedented in historical times; a civilization-ending impactor 2 km in diameter; and a K-T boundary extinctor (10–15 km in diameter). Regarding the consequences of such impacts, how do we know what will happen if the Earth is struck by a 200 m, 2 km, or >10 km body?

CONSEQUENCES OF IMPACTS

Environmental effects

Studies of the modern-day impact hazard have greatly augmented our understanding of the consequences of impacts, probably more so than have analogous studies of the physical, chemical, environmental, and biological effects of giant impacts in a K-T context. Studies of the modern-day hazard (cf. Adushkin and Nemchinov, 1994) have usually focused on the dangerous objects that are most likely to strike, those ranging from producers of giant tsunamis (~200 m diameter, ~1000 Mt explosive yield) to the civilization enders (~2 km diameter, 10^5 Mt), which involve modest extrapolations from weapons tests and the Tunguska event. A reality check, the impact of Comet Shoemaker-Levy 9 into Jupiter in 1994 (roughly equivalent to the ~2 km terrestrial case because of the much higher impact velocity at Jupiter), was extensively researched and applied to the Near Earth Asteroids hazard (cf. Boslough and Crawford,

TABLE 1. CHANCES OF EVENT HAPPENING IN SPECIFIED DURATION

	Human-Scale	Historical		Geological		Planetary
Object (diameter)	1 yr	100 yr	10,000 yr	1 m.y.	100 m.y.	4 b.y.
Cretaceous–Tertiary extinctor (10–15 km)	10^{-8}	10^{-6}	10^{-4}	1%	50%	100%
Civilization ender (2 km)	10^{-6}	10^{-4}	1%	50%	100%	100%
Huge tsunami (200 m)	10^{-4}	1%	50%	100%	100%	100%

1997). Such research has also provided a guide for extrapolating to the far more energetic case of the K-T boundary impact. The latest, most comprehensive review of the environmental consequences of impacts, ranging from 20 m to 20 km diameter ($1–10^9$ Mt), is that of Toon et al. (1997).

The first salient fact is that the impact of a cosmic body with Earth, whether at 15 or 25 km/s (or sometimes greater speeds for comets), essentially causes an explosion: an instantaneous conversion of the kinetic energy of the impactor into fragmentation, comminution, and cratering of the substrate; heating, melting, and vaporization of the projectile and target materials; kinetic energy of cratering ejecta; seismic shock waves penetrating the planet; and other types of destructive energy. Precisely how the kinetic energy is partitioned into the various forms of energy is the subject of continuing research, but we only have to look at the now many-decades-old sites of nuclear weapons tests to understand the general idea. Modern computer codes reliably reproduce the weapons tests and, based on sound physics, can be extrapolated robustly to the energy scales of civilization-ending impacts and perhaps even to mass extinctors.

The second salient fact is that a very significant fraction of the energy from an impact is dissipated in the ecosphere, the thin shell of air, water, and surface rocks and soils whose constancy sustains and nurtures life. The Earth as a planetary body has been unfazed by any impacts subsequent to the colossal interplanetary collision that is believed to have formed our Moon. The geologic record is only marginally perturbed by even the largest post-late heavy bombardment impacts: witness the general obscurity of the famous clay layer at the K-T boundary. The boundary is readily recognized by the permanent change in the diversity of species, but it is not prominent as a geologic feature (the centimeter-scale layer is dwarfed by ordinary sedimentation and erosion and by faulting and other pervasive effects of tectonism and volcanism). However, our thin ecosphere is exceptionally subject to damage and instantaneous modification by events of these magnitudes, even if only a tiny fraction of the kinetic energy of the impactor is partitioned into the atmosphere during the bolide phase (passage of the impactor through the atmosphere), during the explosion, and during the subsequent ejecta plume phase.

A final fact about consequences of impacts is that those that exceed the relevant threshold sizes (dependent on the particular consequence) necessarily distribute their consequences globally: while the greatest damage is obviously at ground zero, the stratosphere is badly polluted with dust on a global scale from impacts exceeding 10^5 Mt (1 km diameter), glowing ejecta are distributed globally from impacts exceeding 10^8 Mt (15 km diameter), and even seismic shock waves may reach moderately damaging proportions on a global scale for impacts of 10^8 Mt scale (K-T level). Even much smaller impacts (e.g., by a 200 m impactor), if into the ocean, can cause devastation thousands of kilometers away due to the efficient transmission of energy to great distances by tsunamis (Ward and Asphaug, 2000). In normal times, the distributive character of air and water is what lubricates our world, maintains chemical balance, and sustains life. In times of catastrophe, however, which overwhelm the modest mass of the atmosphere and ocean and their thermal and chemical balances, these media distribute poisons, sun-darkening dust and aerosols, and meteorological and climatological consequences around the globe. Rebound from past catastrophes that have afflicted civilization (e.g., World War II) have often depended on some portions of the planet remaining unaffected by the localized or regional devastation, thus serving as nuclei of recovery. In the case of a sufficiently large impact, there are essentially no unaffected refugia where life continues normally.

Consider the Comet Shoemaker-Levy 9 impact into Jupiter in 1994: with the kinetic energies roughly that of a civilization-ending impact on Earth, the largest comet fragments created immense, black patches in Jupiter's stratosphere (certainly appreciably dimming the sunlight beneath); several of them exceeded the size of the entire planet Earth and persisted for months (Chapman, 1995).

Precisely what dominant environmental consequences arise from impacts is less certain than the generalizations just listed. Certainly the vagaries of weather forecasting and of other contemporary forecasts of environmental scenarios (e.g., global warming) engender an understandable skepticism among the public about the predictive sciences (cf. Sarewitz et al., 2000). However, the magnitude of a major impact is so enormous compared with the environmental perturbations resulting from twentieth and twenty-first century civilization, that the kinds of uncertainties that plague the other predictions are overwhelmed. Furthermore, because there are so many separate phenomena, the synergies among them, which are difficult to model, probably lead to conditions appreciably worse than the simple addition of their separate effects. If one or two of them are less effective than initially calculated, there remain numerous other damaging consequences. For example, estimates of the production of nitric acid, once thought to be a primary environmental effect of a K-T-scale impact, have more recently waned even as sulfuric acid has received greater attention due to the probable anhydrite-rich substrate near Chicxulub (Pope et al., 1994).

The complete suite of consequences for a 2 km impactor and for a 10–15 km impactor, primarily as gleaned from the comprehensive review of Toon et al. (1997), is summarized in Table 2, supplemented in some cases by insights from other, more recent work. I have left out less significant, more localized damage (e.g., blast effects near ground zero), less well understood effects (general toxicity of the environment and effects on ocean chemistry), and secondary and long-lasting effects.

Although there are significant uncertainties in some of these results, the inevitability of most of the effects within the range of impactor scales we are considering is assured. Several of the effects may independently range from global deterioration of the biosphere (for 2 km impactors) to massive destruction of the biosphere (for K-T-scale impacts). Some of the effects are complementary, e.g., the dramatic cooling effects of impact winter would be moderated near ocean shores due to the ocean's heat capacity (Covey et al., 1994); however, these are the regions that would be inundated and scoured by tsunamis. The tabulated consequences acting in concert (along with other effects not yet fully evaluated), and extended by the less certain, longer term consequences for the chemistry and temperature of the atmosphere and the ocean, would make life on Earth following a big impact horrific.

Civilization-ending impact

The consequences of a civilization-ending impact can dwarf the environmental effects of historical environmental catastrophes, such as the so-called year without summer due to the massive Tambora volcanic eruption in 1815 as well as nuclear winter scenarios envisioned to result from all-out nuclear war (discounting the immediate and long-lasting radiation effects of the latter). An impact is far more efficient than nuclear war (or volcanic explosions) at polluting the stratosphere, despite the fact that other kinds of damage are far more concentrated in one locality in an impact. The most dramatic consequence for modern civilization seems to be the prospect that all agriculture would be lost for a year. Given ongoing episodes of Third World starvation that occur even under the optimized international food-distribution systems in stable times, it seems likely that a sudden impact by a kilometer-scale comet or 2 km asteroid would lead to mass starvation of a sizeable fraction of the world's population.

The end-game of such a scenario naturally involves highly uncertain speculation about the longer term response of the ecosphere, of corporate, national, and international infrastructures, and of the global economic system. Some commentators view civilization as inherently fragile. Human beings have moved away from nature and lack knowledge about survival in the absence of manufactured goods and retail stores. Technology has become highly specialized and is generally inaccessible and incomprehensible to nonspecialists. American society proved to be astonishingly vulnerable to terrorist acts in late 2001, which had objective consequences comparable to one month of automobile traffic fatalities. The network of interdependencies among nations is fragile, even absent a global calamity. A breakdown of social order (like that postulated in the aftermath of a comet strike in *Lucifer's Hammer*; Niven and Pournelle, 1977) is viewed by some as inevitable, probably leading to conflicts and wars on local to global scales (and modern warfare

TABLE 2. MAGNITUDES OF SEVERAL KINDS OF ENVIRONMENTAL CONSEQUENCES FOR TWO SIZES OF IMPACTORS

Chief environmental consequences of impacts	Civilization ender (2 km)	Cretaceous–Tertiary extinctor (10–15 km)
Fires ignited by fireball and/or reentering ejecta	Fires ignited only within hundreds of kilometers of ground zero.	Fires ignited globally; global firestorm assured (Wolbach et al., 1988).
Stratospheric dust obscures sunlight	Sunlight drops to "very cloudy day" (nearly globally); global agriculture threatened by summertime freezes.	Global night; vision is impossible. Severe, multi-year "impact winter."
Other atmospheric effects: sulfate aerosols, water injected into stratosphere, ozone layer destruction, nitric acid, smoke.	Sulfates and smoke augment effects of dust; ozone layer may be destroyed.	Synergy of all factors yields decade-long winter. Approaches level that would acidify oceans (more likely by sulfuric acid than nitric acid).
Earthquakes	Significant damage within hundreds of kilometers of ground zero.	Modest to moderate damage globally.
Tsunamis	Shorelines of proximate ocean flooded inland tens of kilometers.	Primary and secondary tsunami flood most shorelines ~100 km inland, inundating low-lying areas worldwide.

has become *very* dangerous). Such fragility could easily lead from an impact catastrophe to the death of most of the world's population and a long-lasting Dark Ages.

However, other commentators believe that civilization is robust. Frequently, the human spirit rises to meet challenges that seem overwhelming. Cooperation rather than social disintegration seems more likely to some. There are technological refugia (e.g., bomb shelters) and other forms of mitigating the disaster, especially if there is some warning (e.g., food supplies to outlast the darkness could be grown and stored, given a decade's warning, and thanks to the Spaceguard Survey, warning of an impact years to decades in advance is increasingly likely). Human history has demonstrated society's ability to recover from such holocausts as plague and World War II (although less affected peoples and nations contributed to recovery from World War II, which might not be the case in a truly global catastrophe).

Extrapolation to K-T scale impact

With increasing size of impactor, the magnitude of the catastrophe grows toward the scale of a K-T boundary event (with a thousand times the destructive energy of the civilization-threatening event just discussed), and the certainty that, not only would civilization collapse, but the human species would be rendered extinct. Who could survive? Even a well-trained survivalist, capable of living off desert lands in perpetuity, would be overwhelmed by months (not to mention years) of trying to survive in a burned, denuded, bitterly cold, perpetually dark, and poisoned environment. To even try to live off the land and the dregs of a destroyed civilization, an individual would have to have survived (in some deep cave or other shelter somewhere) the initial calamity of a global firestorm, global earthquakes, and other immediate traumas of the impact. How would land-based animals, or complex plants, be any more successful at surviving? Oceanic life would be buffered from the fire, but would still be subject to changes in chemistry and, eventually, temperature, which would be pervasively distributed throughout the waters, with adequate refugia being even more difficult to imagine.

From the perspective of a typical individual (human, animal, plant), survivability from a K-T-scale event is impossible to imagine. However, lessons from the aftermath and recovery of local populations following the Mount St. Helen's eruption and evidence that some species have evolved accidental protections from otherwise highly lethal environments (including extreme temperatures and even high doses of radiation), suggest why the K-T event did not doom all life larger than microbial. To understand such survivability, one must concentrate on *exceptional* environments, most readily imagined by thinking of the world we know, including its special environmental niches and microclimates. Presumably analogous circumstances existed in the past.

An example of such an exceptional environmental niche might be a small herd happening to be next to a thermal spring, and thus luckily in a much better position to survive a multiyear winter than most individuals of the same species; especially so if the spring happens to be deep within a cave where the lucky herd avoided being scorched during the initial postimpact firestorm and was thermally buffered from the multiyear winter. If the cave with springs happened, also, to be on a far-offshore island perhaps shielded from the glowing ejecta by a thick overcast at the time of impact, a small ecosystem of animals and plants might have temporarily survived. All would be lost if that island were subsequently submerged by the impact-generated tsunami or by storms generated by catastrophic meteorological changes. But perhaps not; perhaps the island is perched high above sea level and/or is very far from ground zero. This hypothetical concatenation of lucky circumstances puts the lucky herd a few steps up the ladder of potential survival, although many more environmental challenges must still be overcome to assure long-lasting survival and repopulation of the species. Through such fortuitous circumstances in an exceptional refugium, one can imagine that small reproductive groups might permit the survival of certain lucky species, even if 99.99999% of individual species members have died. That is presumably what happened 65 Ma.

PERCEPTIONS OF RISK

The impact hazard has received some bad press in recent years, giving the subject a certain "Chicken Little" unreality. To underscore the robustness of my central message, I address the issues that affect individual (and society's) perception of the risks associated with the impact hazard. Among the most important are the following.

1. The failure to grasp the meaning of low-level probabilities or of randomness.
2. The fact that ordinarily negligible errors can overwhelm the "signal" of a low-probability event, requiring exceptional procedures for handling calculations and reporting of low-probability events.
3. The failure to understand that scientific research (in this arena, especially) is an ever-improving process and that retracted predictions of impacts or near misses are the usual outcomes of this research, and generally do not imply that mistakes have been made.

In the literature of the psychology of risk perception (e.g., see Cole, 1998), it is commonplace that the human brain finds it inherently difficult to grasp the meaning of probabilities outside of the range of our practical experience. The 1 in 649 739 chance of being dealt a royal flush in poker (not to mention winning a national lottery) is lower than the chance that the Earth will be struck by a civilization-ending asteroid next year. Few gamblers could imagine worrying about the end of everything and everyone they know and love while they still harbor a real hope of beating the odds. People also fear that they may die by several other frightening causes less likely than that of being killed by an impact catastrophe, including death by a wild animal, lightning, or tornado. Companies, governments, and citizens apply great pressure for increased airline safety, despite the fact that an individual American is more likely to die as a result of an asteroid impact than by jetliner crash. Extremely dangerous activities (far exceeding dangers from airplanes or asteroids), however, such as smoking or driving automobiles, or leading a sedentary life, are readily tolerated and rationalized.

Another common confusion involves misunderstanding that the typical waiting time until the next impact (a few hundred thousand years for the end-civilization impact) justifies current inaction. (A related, common confusion familiar to geologists is the layperson's expectation that one can ignore the possibility of a flood because "the hundred-year flood just happened two years ago.") The impact could happen just as readily next year as in some particular year tens of thousands of years from now.

The history of widely publicized impact scares during the past decade may be leading to a "boy who cries wolf" skepticism about the robustness of astronomers' observations and calculations about impact probabilities. Despite attempts to improve, regularize, and simplify the reporting of inherently difficult to understand results to the public (e.g., through de facto adoption of the Torino scale [Binzel, 2000], analogous to the Richter scale for earthquakes, to categorize predictions of possible future impacts), there continue to be headlines about dangerous impacts in the next decades, generally immediately followed by what are perceived as retractions. Several factors, beyond the commonplace hyperbole and misreporting by news media, contribute to these unfortunate perceptions.

Consider what is happening in interplanetary space and in astronomical observatories. The Earth is in a cosmic shooting gallery, although space is very big, so nothing consequential hits Earth very often. During the past three decades, and especially during the past five years, astronomers have begun to scan the skies for asteroids, especially the ones more likely to hit (e.g., not asteroids in the main asteroid belt, most of which are safely there "forever" and all of which are safely there for millennia). Near Earth Asteroids are found as an unknown, uncharted star on a photographic plate or, more recently, on a charge-coupled device (CCD) image. They are confirmed when, after several exposures, they are found to be moving at an appropriate rate (not as fast as an airplane or satellite, but not so slowly as a main-belt asteroid or distant comet) during the course of the night. After observations over the course of a few weeks (provided skies are clear and the patch of sky is in the coverage area of one of the photographic search telescopes), positions of the object are established well enough to calculate an approximate orbit.

While most such preliminary orbits do not permit the asteroid to come anywhere near the Earth in the foreseeable future (in which case the future impact probability is exactly zero), a small fraction of such orbits, especially when propagated forward in time a few decades, include the Earth in the large volume of space that is within the very broad error bars associated with the preliminary orbit. The chances of impact may even be smaller than the chance of a random, thus far undiscovered object hitting the Earth, but at least there is now a known date or dates in the future when such a specific object could conceivably hit; it thus bears monitoring in the future.

After more weeks of additional observations of this still-threatening object, or possibly after discovery of a preexisting observation of it in an archive (that had not previously been successfully linked with other observations to compute a preliminary orbit), the preliminary orbit can be refined and the error bars reduced. In most such cases, the refined orbits no longer include the Earth within uncertainties, and the probability of impact goes to zero. Very occasionally the refined orbit narrows down to a zone that still includes the Earth, and the probability of impact goes up, perhaps to better than 1 chance in a 1 000 000 (for a 1-km-diameter asteroid) or 1 chance in 10 000 (for a 100 m body), which merits moving it from 0 on the Torino scale (meaning roughly equivalent to the background chance of unknown asteroids striking the Earth) to 1 (events meriting careful monitoring). Such cases have been happening a couple of times a year lately, and they may happen more frequently as search techniques advance.

A Torino scale rating of 1 (or higher) generates considerable interest in the media and within the astronomical community. An automatic review of the calculations by a Working Group of the International Astronomical Union (IAU) commences, and observers around the world focus on the potential impactor with urgency, generating new observations or discoveries of archived observations. Commonly, within a few days, the refined data shrink the error bars and an accurate orbit can now be computed. Almost always, the chance of impact reverts to exactly zero and an "all clear" is announced, which the media, having just published news of an impact possibility a few days earlier, tend to call a retraction. The possibility exists, however, although it has never happened yet and is not likely to, that the accurate orbit predicts—now with much higher likelihood, perhaps certainty—a future impact. That, after all, is the purpose of the search. We already know that there is only a one in a few thousand chance of impact of a kilometer-sized body sometime this century, so we expect that refined orbits of new discoveries will continue to move toward zero probability impact. However, there are bound to be a few cases a year in the intermediate stage of orbit improvement that temporarily swing as high as 1 on the Torino scale, meriting attention for a while.

The normal routine described here illustrates why media discussion (e.g., "it is not going to hit after all") misrepresents the Spaceguard search process, although there have been surprises and even mistakes. A surprise occurred in October–November 2000, when an asteroid was calculated to have an astonishingly high 1 in 500 chance of impacting the Earth 30 years hence. The body was faint, hence small, but plausibly of Tunguska size, hence meriting a 1 on the Torino scale. The IAU, following its mandated 72 hour review process, reported confirmation of the calculation; unfortunately, just hours later an earlier observation was found, proving that the impact would not happen. The news media had a field day with the "correction." Further investigation revealed that the object was, in all probability, a highly reflective old booster rocket from the early 1970s. Not only is it hollow, but it is much smaller than had been estimated, and constitutes no danger at all if it is to hit the Earth, which, indeed, seems likely to happen within some thousands of years. Its surprisingly Earth-like orbit would be a strange one for a real asteroid, but typical of space junk. In the future, astronomers are likely to be more aware of the possibility of being confused by space debris.

Much of the skepticism about astronomers' predictions is the legacy of an actual mistake made in 1998 (cf. Chapman, 2000), when an internationally respected astronomer announced that a civilization-ending asteroid, 1997 XF11, would come spectacularly close to the Earth in 2028, "virtually certain" to pass within the orbit of the Moon but nominally only 40 000 km away, implying an impact probability as high as 0.1%. The calculations were faulty. Data archived by the astronomer during several previous months were sufficient to calculate an impact probability of essentially zero (about 1 chance in 10^{42}), but he was excited and failed to check his results with colleagues before issuing a press information statement that generated headlines around the world. Once again, astronomers rushed to their archived images and found positions for 1997 XF11 that showed it to be in an orbit such that it could not possibly hit the Earth, but would actually pass 2.5 times farther away than the Moon in 2028. Unlike the nominal process described here, this time the original prediction was just wrong.

An unappreciated reality affecting predictions of very low probability occurrences is that the probability of making an error in calculating such a probability is much larger than the probability itself. Ordinary human care, resulting perhaps in 99% reliability, doesn't suffice when trying to reduce the already extremely tiny chances of an airliner accident, or in assuredly calculating a low-probability asteroid impact. In the operations arena, the engineering discipline of surety systems analysis has been devised to build in safeguards against even the extremely low probability concatenation of improbable events that after the fact analysis often shows to be the cause of rare accidents, e.g., airliner crashes or the Three Mile Island nuclear accident. Surety involves "out of the box" thinking about exceptionally unusual circumstances, human factors analysis, and multiple closed-loop redundancies.

In asteroid astronomy, similar procedures must be implemented to avoid cries of "wolf!" At the time of the 1998 mistaken announcement, given the known impact probabilities, it was much more likely that the astronomer had made a mistake than that the newly implemented Spaceguard Survey had already found an asteroid, large enough to destroy human civilization, with a significant chance of striking within our lifetimes. Indeed, the astronomer was mistaken. The calculation-checking procedures of the IAU were subsequently developed, in part, to minimize the chances of future mistakes. Henceforth, we may hope that reported possibilities of future impacts are at least objective, even if they will almost certainly quickly evolve to zero.

In conclusion, the widespread dissension within the astronomical community concerning issues of impact probabilities and the outright skepticism sometimes expressed in the media are an inevitable result of misunderstandings over how to understand and communicate about unfamiliarly tiny probabilities. They in no way should be taken to undercut the robust understanding of how often the Earth is likely to be struck by cosmic projectiles of various sizes.

There is a related analogy relevant to how geologists and paleontologists, facing rare crises in Earth history, should evaluate evidence in the geologic record. Given the unimaginably grotesque consequences of large asteroid impacts, which have certainly happened, as well as the range of lesser but nonetheless dramatic catastrophes occasionally posed by volcanism, tectonics, and potential climatological instabilities, we must step "out of the box" of our normal world and think realistically about how biological populations and ecosystems might have been affected by such rare disasters. The rules are different at such times from anything we have personally witnessed or can even easily imagine.

UNDERSTANDING CRISES IN EARTH HISTORY

Comparisons of natural hazards

The first lesson for historical geology from studies of how the impact hazard affects our modern world is to understand the almost unfathomable differences in scale of impacts of various sized asteroids. Even the "small" ones have enormous consequences beyond our experiences. The 1908 Tunguska impact unleashed an explosive energy equal to more than a thousand Hiroshima bombs and only a few times less than the largest ever bomb test. Tunguska devastated ~1000 km^2 of Siberian forest or ~0.001% of the land area of the Earth. In contrast, the energy of the K-T boundary impact was 10^7 times greater than Tunguska; one could think of every 1000 km^2 land unit on our planet being allocated 500 times the energy that leveled the Tunguska region. Actually the destructive processes change with scale of impact and the consequences vary with distance from ground zero, but clearly, even if the comparative destructive efficiencies are extremely low, our fragile ecosphere has to absorb an enormous amount of destructive energy within an hour or two of a K-T-scale impact.

Figure 1 is a highly schematic representation of the comparative consequences of various kinds of accidents and natural disasters, represented by human lethality. The vertical axis represents the annualized world fatality rate from various types of accidents and disasters; the more serious sources of death plot higher on the graph. The horizontal axis (deaths per event) depicts an important qualitative difference between the various accidents and disasters. Automobile accidents kill many people; they happen frequently, but generally kill only a few at a time. Accidents involving buses, trains, ocean vessels, and airplanes have the potential for killing many more people at a time, and occasionally they do, which is why their curves extend somewhat to the right. While natural disasters, like a small avalanche or a minor earthquake, can kill just a few people, many deaths from natural disasters result from rather rare, big events. For example, between 10^5 and 2×10^6 people died in each of the 11 worst natural disasters (chiefly earthquakes, floods, and cyclones) during the period 1900–1987 (Munich Reinsurance Company, 1988), even though many years passed with no natural disasters even approaching these rates of lethality.

The impact hazard represents another jump toward extremely high lethality per event, but extreme rarity. Averaged over time, the lethality (height on the diagram) is comparable with many other individual kinds of natural disasters, although less than for some kinds of accidents. (War, famine, and especially disease greatly exceed both natural disasters and accidents as the chief killers.) Qualitatively, the impact hazard is very different from anything else plotted: it is the only hazard capable of killing hundreds of millions of people, or even the entire world population, in one event.

Of course, nuclear war has been hypothesized as having the potential to reach this level of death and destruction. However, it presumably has no relevance for understanding past mass extinctions. Conceivably, some virulent disease could break out and decimate, or even eradicate, the human species; this also is probably not relevant to understanding mass extinctions because diseases are normally species specific and are not easily spread among numerous species, although breakdowns of ecological systems could conceivably magnify the consequences of such an outbreak. A nearby astrophysical disaster (supernova) cannot be completely ruled out, although it would be very unlikely.

Most geophysical natural hazards necessarily have natural upper bounds to their catastrophic potential. For example, Chinnery and North (1975, p. 1198) stated “There are good reasons for believing that there must be an upper bound to earthquake M_o values, due to the geometry of seismic zones and the strength of crustal material.” The only possible competitor for asteroid impacts is volcanism. It has been argued that monstrous volcanic explosions (cf. Rampino et al., 1988), dwarfing those recorded during human history but occasionally recognizable in the geologic record, could approach the magnitude of a kilometer-scale asteroid impact. This topic deserves further research (see double-headed arrow in Fig. 1 indicating conservative and liberal possibilities for the magnitude of large volcanic events), but it also seems unlikely to apply to mass extinctions. There are inherent limitations, imposed by the strength of the Earth’s crustal rocks, in the possible magnitude to which pent-up volcanic energy can rise before breaking through. Therefore, there must be an upper limit to the magnitude of a volcanic explosion; the Toba event of ca. 75 ka, recorded in the geologic record, may be as big as they get, and no mass extinction was associated with that.

The asteroid and comet size distributions, however, continue to larger sizes without end. While only a few Earth-approaching asteroids currently exceed the size of the K-T boundary impactor (none of them can strike the Earth in the near future, although Earth approachers are replenished on time scales of millions to tens of millions of years), an unknown comet could arrive with a warning of only months or a year, and it could have an immense size. Comet Hale-Bopp, prominent in the sky in 1997, was estimated to have a diameter of at least 25 km and perhaps as large as 70 km. It came within the Earth’s orbit, although on the other side of the solar system. Had it struck, with its energy of tens to hundreds of K-T boundary impactors at once, it might have sterilized our planet of all but microbial life. Thus no hazard other than cosmic impacts has the possibility of conceivably eradicating humanity in a single event. Fortunately, the odds are very small that such an event will happen soon.

Some perspectives on the past from today

Looking to Earth history, however, extremely small odds during a human lifetime become virtual certainties on a time scale of geologic epochs. The odds of any of the three examples of impactors (Table 1; 200 m, 2 km, 10–15 km) striking during a year—the usual temporal measure for human hazards—are very small, ranging from 10^{-4} to 10^{-8}. However, all of them are *certain* to happen on geologic time scales. There have been repeated impacts resulting in huge tsunamis during Earth’s history, and one may even have struck during human history (conceivably contributing to one or more of the great flood myths). A “civilization ender” is likely to strike a couple of times every 10^6 yr (which means $\sim$100 of them since the time of the K-T boundary). They have necessarily caused “bad years” for most species dependent, directly or indirectly, on a summer season. K-T scale impactors have surely struck several to a dozen times during the Phanerozoic, and it is natural to try to associate the worst crises in Earth history with those randomly timed but irrefutable cataclysmic events of the past. What is rare with almost negligible chances on a human time scale (thus permitting international society to largely ignore this threat to its very existence) becomes a certain fact in the context of interpreting the paleontologic record. Impacts cannot be ignored: they have happened, and the larger among them were unimaginably devastating.

There are some ways of thinking about mass-extinction events that can be seen as unrealistic if viewed from the perspective of a modern-day catastrophe. We must especially heed the variety of things that can happen within lengthy durations that are unresolvable in the geologic record. We must not attribute to the global ecosystem, but rather to exceptional refugia, the characteristics that permitted some species to survive a mass extinction. The following anecdotes from discussions at the 2000 Snowbird conference exemplify how we must change our thinking.

The difference in time scales relevant to the survival of a species in the face of a sudden, global, environmental catastrophe compared with that resolvable in the geologic record is profound. The survivability of animals may depend on migrations over enormous distances taking just weeks or months, time scales orders of magnitude shorter than the precision of dating the stratigraphic age of fossils.

A speaker at this conference suggested that subfreezing temperatures lasting months would be incompatible with the survival of certain reptiles. But that would not be true if a few reptiles survived next to a thermal hot springs in a favorably located cave. One must guard against attributing to the environments of a few exceptional refugia the average conditions of the Earth during a global environmental crisis.

There is a tendency to confuse killing or survival of a species with general death or survival of individuals during a crisis. Thus one speaker discussed the theoretical possibility that small carnivorous dinosaurs might have been able to survive on mammals, lizards, and other species that made it through the extinction. In all probability, however, this is not even theoretically possible: in a devastated world, where virtually every individual mammal presumably was killed, the survivors that enabled continuance of some mammal species were probably small groups in totally exceptional refugia, hardly a findable food source for some carnivores stumbling blindly through the darkness.

Importance of sudden changes for mass extinctions

Traditionally, mass extinctions have been ascribed to various changes in the environment that evolve extremely slowly compared with the sudden events (impacts, volcanic explosions) that I have discussed. Sea-level changes, chemical and thermal changes to the oceans, global warming, glaciations, and hotspot volcanic outpourings have all have traditionally been interpreted to evolve over durations ranging from tens of thousands of years to millions of years. Even recently hypothesized runaway geophysical processes commence on time scales that are long compared with the characteristic time scales of impact devastation, i.e., minutes to years. To me, it seems obvious that a sudden event (happening on a time scale, like months, that is short compared with the lifetime of an individual animal or plant) would be a far more potent cause of mass death and a possible mass extinction than changes, almost no matter how great, that evolve over centuries, millennia, or even millions of years. Here, a modern-day perspective is helpful.

A disaster, in human terms, is necessarily something that happens during a day, or perhaps over months or a year, but never over decades or centuries. After all, 100% of human beings now alive will die during the next 120 years or so, but that is considered normal, not a catastrophe. A powerful hurricane that strikes Florida can be a major natural disaster, but if waters rise and flood Florida during the next half-century (perhaps resulting from global warming), then people and enterprises can calmly move out of Florida at the rate that they moved in during the past half-century; it would be one of the usual ebbs and flows of economic and societal change, not a catastrophe.

As we look at Earth history, we must realize that species will be much more seriously affected by a catastrophe that is short compared with the reproductive cycle of individuals, and globally pervasive, two unique attributes of impacts. Some of the most powerful effects of impacts are over within the first few hours; most of the others are over within a few years. While much longer lasting effects will certainly ensue, and are recognized in the post-K-T geologic record, they are, like other slowly acting environmental changes, of little consequence to mass extinctions, no matter how much they may inhibit recovery and radiation of new species. For impacts over certain thresholds (that vary depending on the specific consequence; see Table 2), the effects are global in extent, notwithstanding possibilities that small refugia may be less affected. If all individuals starve, freeze, and die within a year of an impact holocaust, how will the species reproduce and survive? Adaptation to such radical environmental shocks is practically impossible.

The onset of an ice age is something that can be adapted to. (Walls of ice never arrive suddenly in suburban New Jersey, as depicted in Thornton Wilder's play *The Skin of Our Teeth*.) Seas don't suddenly regress, dramatically decreasing certain ecological niches worldwide, within the lifetimes of aquatic species. Species can migrate and/or develop new behaviors. Even if competition results in stresses and lowered population numbers, the survival of small breeding populations within such evolving ecosystems seems much more likely than in the instantly scorched, but frozen Earth aftermath of an impact. One of the most popular causes for mass extinctions discussed at the 2000 Vienna conference are episodes millions of years long of enhanced hotspot volcanism in certain localities on Earth. I cannot understand why anyone would regard such localized formation of a volcanic province like the Deccan Traps as conceivably resulting in a mass extinction. What are the killing mechanisms from such a slowly evolving process on the opposite side of the planet? Localized volcanism enhanced by factors of many compared with the modern rate may show up prominently in the geologic record, but the modest global ecological ramifications would be readily adapted to by migrations, evolutionary change, and other long-term responses.

Understanding that slow-acting climatological changes are impotent as causes of mass extinctions, some researchers have hypothesized that there are possibilities for natural, rapid instabilities on Earth, including sudden melting and destruction of polar ice caps, great landslides on continental shelves, and dramatic changes in the carbon dioxide budget. Such events could possibly stress populations in ways not readily responded to, but even they are much slower acting and less dramatic in their consequences than are impacts. They rely on such factors as rising sea levels (which fail to severely affect habitats far from shorelines) and changing climates. Yet none of them transmit their devastating effects at the speed of many kilometers per second, spreading around the globe in a couple of hours, and none of them can be as globally and suddenly effective in changing the climate as the instantaneous and efficient injection of dust and aerosols into the stratosphere, greatly dimming or blocking out the Sun around the entire globe within a matter of weeks and lasting for many months to many years.

Even despite recent advances (S.A. Bowring, this conference), resolvable time scales concerning ancient events in the geologic record are long compared with human time scales. It is understandable, therefore, that geologists try to measure and think about environmental changes over such resolvable times. However, by imagining a multikilometer asteroid impact occurring today, in our modern built-up and natural world, we become much more aware of the amazingly sudden and profound changes that would present dramatic obstacles to survivability.

Huge impacts, which were nearly instantaneous in their globally devastating effects, have certainly occurred several times since the Precambrian. Their potency in causing the nearly instantaneous collapse of ecosystems (within minutes to months) dramatically exceeds any other suggested mechanism for mass extinction. The smoking guns (like extant, nonsubducted craters) become less likely to remain in the geologic record as we search back in time, but should not be required as evidence for impact, given the inevitability that the monster impacts have occurred. Other evidences of the K-T boundary impact, including the famous iridium excess, are not necessary outcomes of all major impacts (e.g., iridium content varies among impactors, and survival of projectile material is problematic, depending on the velocity and angle of impact). The impacts have occurred and have the unique attribute of sudden, global simultaneity. I think it is no coincidence that, as the techniques for making temporal measurements improve, the time scales associated with the largest mass extinctions (like the Permian-Triassic extinction; D.H. Erwin et al., this volume) continually shrink.

The huge impacts were so instantly awful, they must have left a paleontological record, and must have caused mass extinctions of some scale. It is a testimony to the resilience of life that, through localized, exceptional circumstances, breeding populations survived so that enough species managed to make it through the year-long frozen night of terror and death. It then becomes problematic that any other gradualistic geologic or environmental process could have played such a significant role, if any at all, in mass extinctions. If a total lack of evidence (e.g., of a layer of shocked dust) requires searching for another cause in the case of a particular mass extinction, only then are we compelled to turn to other improbable but still instantaneous causes, such as an immense volcanic explosion or supernova.

Raup's idea that the record of extinction reflects the cosmic impactor size distribution, and that impacts may be the cause of essentially all mass extinctions, was actually first enunciated in 1980 (Alvarez et al., 1980b, p. 2):

> It is reasonable to assume that the Permian-Triassic (P-T) and K-T extinctions were caused by large Earth-crossers, while lesser extinctions may have been caused by more numerous smaller asteroids. If so, the severity vs. frequency should relate to the size vs. number of Earth-crossing objects.

From the perspective of modern research on the impact hazard, it seems even more likely now that impacts have been the dominant cause of mass extinctions during the Phanerozoic.

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REFERENCES CITED

Adushkin, V.V., and Nemchinov, I.V., 1994, Consequences of impacts of cosmic bodies on the surface of the earth, *in* Gehrels, T., ed., Hazards due to comets and asteroids: Tucson, University of Arizona Press, p. 721–778.

Alvarez, L., Alvarez, W., Asaro, F., and Michel, H.V., 1980a, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Science, v. 208, p. 1095–1108.

Alvarez, L.W., Dyson, F., Frosch, R.A., Hunter, P., Meinel, A., Naugle, J., Niehoff, J., Oliver, B.M., Sadin, S.A., and Yardley, J.F., 1980b, Project Spacewatch, *in* Report of New Directions Symposium: Woods Hole, Massachusetts, NASA Advisory Council.

Atkinson, H.H. (Chairman), 2000, UK Government Report of Task Force on Potentially Hazardous Near Earth Objects: British National Space Centre, London (http://www.nearearthobjects.co.uk/index.cfm).

Binzel, R.P., 2000, The Torino Impact Hazard Scale: Planetary and Space Science, v. 48, p. 297–303.

Boslough, M.B.E., and Crawford, D.A., 1997, Shoemaker-Levy 9 and plume-forming collisions on Earth, *in* Remo, J.L., ed., Near-Earth Objects: The United Nations Conference: Annals of the New York Academy of Sciences, v. 822, p. 236–282.

Bottke, W.F., Jedicke, R., Morbidelli, A., Petit, J.-M., and Gladman, B., 2000, Understanding the distribution of Near-Earth Asteroids: Science, v. 288, p. 2190–2194.

Brown, P.G., and 21 others, 2000, The fall, recovery, orbit, and composition of the Tagish Lake meteorite: A new type of carbonaceous chondrite: Science, v. 290, p. 320–325.

Chapman, C.R., 1995, What if? . . . , *in* Spencer, J.R., and Mitton, J., eds., The great comet crash: Cambridge, Cambridge University Press, p. 103–108.

Chapman, C.R., 2000, The asteroid/comet impact hazard: Homo sapiens as dinosaur?, *in* Sarewitz, D., Pielke, R.A., Jr., and Byerly, R., Jr., eds., Prediction: Science, decision making, and the future of nature: Washington, D.C., Island Press, p. 107–134.

Chapman, C.R., and Morrison, D., 1994, Impacts on the earth by asteroids and comets: Assessing the hazard: Nature, v. 367, p. 33–40.

Chinnery, M.A., and North, R.G., 1975, The frequency of very large earthquakes: Science, v. 190, p. 1197–1198.

Cole, K.C., 1998, Calculated risks: Skeptical Inquirer, v. 22, n. 5, p. 32–36.
Covey, C., Thompson, S.L., Weissman, P.R., and MacCracken, M.C., 1994, Global climatic effects of atmospheric dust from an asteroid or comet impact on Earth: Global and Planetary Change, v. 9, 263–273.
Dohnanyi, J.W., 1969, Collisional model of asteroids and their debris: Journal of Geophysical Research, v. 74, p. 2531–2554.
Durda, D.D., Greenberg, R., and Jedicke, R., 1998, Collisional models and scaling laws: A new interpretation of the shape of the main-belt asteroid size distribution: Icarus, v. 135, p. 431–440.
Munich Reinsurance Company (Münchener Rückversicherungs-Gesellschaft), 1988, World Map of Natural Hazards: Munich, 36 p.
Nemtchinov, I.V., Jacobs, C., and Tagliaferri, E., 1997, Analysis of satellite observations of large meteoroid impacts, *in* Remo, J.L., ed., Near-Earth Objects: The United Nations Conference: Annals of the New York Academy of Sciences, v. 822, p. 303–317.
Niven, L., and Pournelle, J., 1977, Lucifer's hammer: Chicago, Playboy Press, 494 p.
Pilcher, C., 1998, Testimony before House Subcommittee on Space and Aeronautics, http://www.house.gov/science/pilcher_05-21.htm.
Piotrowski, S.I., 1953, The collisions of asteroids: Acta Astronautica, ser. A, v. 6, p. 115–138.
Pope, K.O., Baines, K.H., Ocampo, A.C., and Ivanov, B.A., 1994, Impact winter and the Cretaceous/Tertiary extinctions: Results of a Chicxulub asteroid impact model: Earth and Planetary Science Letters, v. 128, p. 716–725.
Rabinowitz, D., Helin, E., Lawrence, K., and Pravdo, S., 2000, A reduced estimate of the number of kilometre-sized near-Earth Asteroids: Nature, v. 403, p. 165–166.
Rampino, M.R., Stothers, R.B., and Self, S., 1988, Volcanic winters: Annual Review of Earth and Planetary Science, v. 16, p. 73–99.
Raup, D.M., 1991, Bad genes or bad luck?: New York, Norton, 210 p.
Sarewitz, D., Pielke, R.A., Jr., and Byerly, R., Jr., editors., 2000, Prediction: Science, decision making, and the future of nature: Washington, D.C., Island Press, 405 p.
Shoemaker, E.M., 1983, Asteroid and comet bombardment of the earth: Annual Review of Earth and Planetary Science, v. 11, p. 461–494.
Stuart, J.S., 2001, A Near-Earth Asteroid population estimate from the LINEAR survey: Science, v. 294, p. 1691–1693.
Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P., and Covey, C., 1997, Environmental perturbations caused by the impacts of asteroids and comets: Reviews of Geophysics, v. 35, p. 41–78.
Veverka, J., and 32 others, 2000, NEAR at Eros: Imaging and spectral results: Science, v. 289, p. 2088–2097.
Ward, S.N., and Asphaug, E., 2000, Asteroid impact tsunami: A probabilistic hazard assessment: Icarus, v. 145, p. 64–78.
Wolbach, W.S., Gilmour, I., Anders, E., Orth, C.J., and Brooks, R.R., 1988, Global fire at the Cretaceous-Tertiary boundary, Nature, v. 334, p. 665–669.

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