by Richard A F Grieve

Impact: a natural hazard in planetary evolution

Bodies in the solar system have been bombarded by interplanetary debris throughout time. In early solar-system history, collisions between proto-planets occurred and one such impact of a Mars-sized object with the proto-Earth may have resulted in the formation of the Moon. For the first 600 million years of geological time, impact was a dominant geological process and shaped the surface and crustal evolution of the terrestrial planets. On Earth, it may also have resulted in the erosion of the atmosphere and massive excursions in temperature that affected the viability of the biosphere. As this early intense flux died off with time, impact played less of a role in planetary evolution. Occasional large-impact events by bodies in the ten kilometre size range, however, continued through the Phanerozoic and at least one resulted in a mass extinction event in the biostratigraphic record. Smaller-impact events by bodies in the one kilometre size range, which occur less than every million years, are of little danger to the global biosphere. However, these impacts could severely affect or even destroy the complex infrastructure of modern human civilizations through the equivalent of a 'nuclear winter'.

Introduction

The solar system is a dynamic environment that has undergone change through geological time. One of the agents of change is impact by interplanetary debris. Currently, this debris ranges from dust-sized particles through kilometre- to tens of kilometre-sized asteroidal and cometary bodies. In early solar system history, this debris was considerably more abundant and contained larger bodies the impact of which resulted in sudden and violent changes by the most catastrophic of all geologic processes. This article attempts to assess the role of impact on the geological and biological evolution of planetary bodies.

The effects of impact are considered for two end-member planetary bodies for which we have considerable information: the Moon and the Earth. The Moon represents a body lacking a shielding atmosphere, with minimum endogenic geological and no biological activity. The Earth represents a body with a shielding atmosphere and with considerable endogenic geological and biological, including human, activity. The hazard presented by the flux of interplanetary debris is some combination of frequency of occurrence and consequences of occurrence. The former can be estimated fairly well. The latter, however, is highly variable, particularly when dealing with complex and poorly understood systems, such as occur on Earth. In major-impact events on the Earth, the impact energy is partitioned not only into the geosphere and/or hydrosphere but a portion is coupled through the atmosphere and thus ultimately into the biosphere.

The Earth has retained only a small sample of the population of impact craters that have formed on its surface. The Moon, on the other hand, has recorded essentially the complete record since ≥ 4000 Ma. Crater counts in combination with isotopic ages of returned lunar samples have established a crater production rate and its variation with geological time. The rate appears to have been relatively constant back to about 3000 Ma, when it begins to rise (figure 1). At times earlier than about 4000 Ma, there appears to be an exponential increase in the rate (figure 1). The actual increase is somewhat speculative, as there is a question as to whether the observable crater population in the ancient lunar highlands accurately reflects all the craters that have been formed, or reflects only those that have not been obliterated by subsequent impacts (Hartmann, 1980; Neukum, 1977). Whatever the case, it is clear that, prior to about 4000 Ma, the earliest flux recorded in the lunar highlands was at least 100 times higher than the present flux. It is against this background, of a decline in both the frequency and the size of impact events with time, that the consequences for planetary evolution are assessed. Although the declining flux is a continuous function, the effects of impact have, for convenience, been separated into three stages: accretion, from about 4600 to 4500 Ma; the period of heavy bombardment following early crustal

Figure 1 Semi-logarithmic plot of variation in impact cratering rate in the Earth-Moon system with time (b.y. = thousand million years). Data on crater counts, for craters larger than 4 km in diameter are from the Moon, A and L are various Apollo and Luna landing sites for which there are isotopic data on surface ages, and the Earth. Solid curves define the uncertainties in the rate due to uncertainties in crater counts and isotopic ages. Shown for comparison is the shape of a constant cratering flux—dashed line.

formation, about 4500–3800 Ma; the period of continuing decline then constant rate of bombardment, from about 3800 Ma to the present. Finally, the special case of the potential hazard of the impact flux to present and future human activity is considered.

Impact and planetary accretion

As there is no direct evidence for the details of planetary accretion, current knowledge is based on models (e.g., Safranov, 1969; Wetherill, 1985). Numerical simulations of planetary accretion envisage the collision and growth of 10^8 – 10^{12} bodies with diameters of around 10 km (Wetherill and Stewart, 1989; Ohtsuki and others, 1988). These asteroid-sized bodies grow rapidly (over 10^4 – 10^5 y) by impact to between 20 and 30 or so embryonic planets with masses of the order of 5×10^{26} g (10% of the mass of the present Earth). At this stage, encounter velocities are relatively low, < 100 m s⁻¹. In addition to embryonic planets, the proto-solar system contains 10^6 – 10^7 bodies in the 10–100 km size range and a tail of fragments < 1 km in diameter produced by the collisions.

This early stage of planetary accretion is believed to be followed by a stage involving truly giant impacts between the embryos. During this next stage, encounter velocities increase to 1–10 km s⁻¹ and a few planetary bodies with masses of about 10^{27} g are formed in 10^6 – 10^8 y. This runaway growth is also suggested by isotopic data (Pepin and Phinney, 1975). In addition to major planetary bodies, there is a residual population of 10–500 km-sized bodies. Although there is no direct evidence for this hypothesis, there is supporting evidence for the collision and disruption of relatively large bodies in the solar system. For example, the photogeological evidence from Voyager 2 suggests that Miranda, a moon of Uranus, some 500 km in diameter, may have been disrupted by major collisions and reaccreted five times since its original formation (Smith and others, 1986). There is also the abundant evidence for large basin-forming impacts on the terrestrial planets, once they had formed and had established a stable crust.

During planetary history, the effects of impacts of the greatest magnitude dominate the cumulative effects of the many more, smaller impacts. In the case of the Earth, the last embryonic planetary collision may have resulted in the formation of the Moon (Hartmann and others, 1986). Previously, hypotheses for the origin of the Moon fell into three groups: capture, fission and coaccretion. None of these satisfy the constraints provided by post-Apollo knowledge of the chemistry and physics of the Earth-Moon system (Wood, 1986).

The hypothesis that the Moon formed by the collision of a large body with Earth, resulting in the ejection of iron-deficient crustal and mantle material which was depleted in volatiles and enriched in refractory elements, was proposed originally by Hartmann and Davis (1975). They suggested that the impact of a body of two lunar masses, with the Earth, would be sufficient. Cameron and Ward (1976) argued that this would be insufficient to account for the high angular momentum of the Earth-Moon system and an impacting body approximately the size of Mars is required. Numerical simulations of such an impact have been carried out, that result in the formation of an Earth-orbiting accretionary disk from which a Moon-like body could form (Benz and others, 1986; Kipp and Melosh, 1986). The consequences of such a giant impact for the proto-Earth would have been severe, and include massive remelting of the Earth and the loss of the original atmosphere (Cameron, 1983). This could explain the differences between the noble gases contents in atmospheres of the Earth and Venus (Donahue and Pollack, 1983).

Impact and early crustal evolution

Following planetary formation, the subsequent high rate of bombardment by the remaining tail of accretionary debris is recorded on the Moon and other terrestrial planets (e.g., Mars, Mercury) and some of the icy satellites of the outer solar system that have pre-

served portions of their earliest crust. It is not recorded on the Earth, because of its high level of internal geological activity and relatively young surface. Due to the age of its crust, the relatively large number of exploration missions and the availability of samples, the Moon is the source of most interpretations of the effects of such an early high flux on geological evolution (Wilhelms, 1987).

The results of the Apollo missions demonstrate the dominance of impact in the nature of the samples from the lunar highlands. Over 90 per cent of the returned samples are impact lithologies, with 30 per cent by volume being impact melt rocks (Ryder, 1981). It is typical for lunar highland breccias to contain clasts of pre-existing breccias and impact melt rocks, indicating that individual samples record several impacts. The dominance of impact as a process for change is also reflected in the age of the lunar highlands samples. The bulk of the near-surface rocks, which are impact products, have ages in the 4000–3800 Ma range (Taylor and others, 1991). Only a few plutonic rocks with ages ≥ 3900 Ma occur in the Apollo collection. Although there is some uncertainty, Monte Carlo simulations indicate that the cumulative thickness of materials ejected from major lunar craters in the lunar highlands is 2–10 km (Hörz and others, 1976). This ballistically transported and mixed layer on the surface of the Moon is referred to as the megaregolith and corresponds to a zone of increasing seismic velocity with depth (Toksöz and others, 1973). Beneath the megaregolith, the lunar crust is believed to be fractured, but essentially autochthonous or in place, to a depth of 20–25 km.

The large multi-ring basins on the Moon define the basic surface dichotomy between lunar anorthositic highlands and younger, in-fill, basaltic maria (Head and Solomon, 1981). They also define the major topographic features of the Moon. For example, the topography associated with Orientale (figure 2), the youngest multi-ring basin at about 3800 Ma and, therefore, the basin with the least topographic relaxation, is up to 11 km. The impact energies released in the formation of impact basins in the 1000 km size range are of the order of 10^{27} – 10^{28} J, 10^6 – 10^7 times the present annual output of internal energy of the Earth. The volume of crust melted in individual basin-forming events is of the order of 10^6 km³ (Lange and Ahrens, 1979). In the case of the 900 km Orientale basin (figure 2), photogeological interpretations suggest that 2×10^5 km³ of this impact melt has remained inside the basin (Head, 1974). Estimates of the amount of ejecta from Orientale are 10^7 km³ (Howard and others, 1974). Although crater ejecta are generally confined to within < 2.5 diameters of the source crater, this still represents essentially hemispheric redistribution of materials in the case of an Orientale-sized impact on the Moon. A small amount of the impact energy, conservatively estimated at 10^{-4} (Schultz and Gault, 1975), is partitioned into seismic energy. For basin-sized impacts, however, this is considerable, 10^{23} J for an Orientale-sized event, and seismic-induced vertical displacements of the order of 10 m or greater are likely.

From gravity data, Bratt and others (1985a) have modelled the deep structure of the interior of large lunar impact basins, which includes crustal thinning and mantle uplift due to the impact process. Following formation, these impact basins localize endogenic geological activity in the form of volcanism and tectonism (Head and Solomon, 1981). In large part, the subsequent local tectonic evolution is the result of the loss of the thermal anomaly produced by post-shock heating and the uplift of isotherms during basin formation. Bratt and others (1985b) estimate this thermal anomaly, following the formation of Orientale, to be of the order of 10^{25} – 10^{26} J and located within 100–200 km from the point of impact. This thermal energy dissipates in about 10^8 – 10^9 y, leading to thermal stresses, crustal fracturing and subsidence. In addition to thermal subsidence, the basins may be loaded by mare volcanics, leading to further subsidence and stress.

The Earth did not escape the formation of large impact basins by the remnants of accretionary debris. There has been considerable speculation as to the potential effects of basin-sized impacts on the Earth. These include major impacts as agents for the formation of both proto-ocean basins (Frey, 1980; Lowman, 1976) and proto-continental nuclei (Goodwin, 1976; Grieve, 1980), as well as potential genetic relations between basin-sized impacts and early komatiite

Figure 2 *Lunar Orbiter photograph of the Orientale Basin on the Moon. This 900 km impact basin is the best preserved and youngest lunar basin at 3800 Ma. As many as 200 basins of this size or larger may have been formed on the Earth between 4500 and 3800 Ma.*

magmas (Green, 1972), certain greenstone terranes (Glikson, 1976) and concentric geological and geophysical patterns in ancient shield areas (Weiblen and Schulz, 1978). The Earth received a higher cratering flux than the Moon because of its greater gravitational attraction. From the lunar cratering rate, and assuming approach velocities of $6\text{--}10\text{ km s}^{-1}$, it is estimated that some 200 impact basins greater than 1000 km were formed on the Earth from 4500 to 3800 Ma (Grieve and others, 1990). The cumulative effect of such a bombardment on the surface and upper crustal rocks of the Earth are unknown. The Earth's earliest crust was either not voluminous or was destroyed by impact and tectonic forces. By analogy with the lunar case, it appears that, regardless of the level of tectonic activity, which was probably high, it is unlikely that few terrestrial surface rocks would have survived intact through this period of heavy bombardment. To a first order, the early Earth would have experienced a series of effects similar to those on the Moon. There will have been, however, some important differences. For example, initial basin formation, with excavation and uplift of mantle material, impact melting, ejection and mixing of crustal material will all have taken place. These processes are due to the physics of the impact processes and are independent of the nature of the planetary body. Impact-related topography, however, will have been less than on the Moon, because of the higher surface gravity and the weaker and thinner lithosphere, and impact-related fracturing will have likely been relatively quickly healed by the hotter and wetter terrestrial crust.

Modelling of the post-impact thermal evolution of 1000 km-sized basins on the early Earth indicates that the thermal anomaly induced by post-shock waste heat and isotherm uplift will persist for $10^7\text{--}10^8\text{ y}$ if heat loss is solely by conduction (Grieve and Parmentier, 1984). This is similar to the lunar case. As noted above, however, the Earth has had a relatively thin lithosphere compared to the

Moon, at any given time in geological history. Thus, heat losses by convection will play a major role following what amounts essentially to the removal of the lithosphere in a major basin-sized impact event on the early Earth. In this case, the rate-controlling parameter in post-impact cooling is the Rayleigh Number, Ra , which determines whether or not convection takes place and, if so, how rapidly. Models of the cooling history of basin-sized events through convection, using finite difference solutions to equations for viscous flow and energy conservation, indicate that initial cooling is very rapid (Grieve and others, 1990). For $Ra = 10^7$, the lithosphere at the centre of the terrestrial impact basin may regain its original thickness in as little as a few million years. With time, the relative importance of convective heat losses diminishes and once heat losses are dominated by conduction, the time required for the thermal anomaly to die to zero is around 10^8 y , regardless of basin size and Rayleigh Number. If the post-basin lithosphere heals itself rapidly, it is unlikely that these major impacts resulted in the basic crustal dichotomy of the Earth (Frey, 1980; Grieve, 1980).

Basin-sized impacts will also have affected the existing atmosphere, hydrosphere and potential biosphere. The vapour plume created by high-velocity ejecta in sufficiently large impacts, can blow-off the atmospheric mass above the tangent plane through the point of impact. Considering the cumulative impact flux from the lunar record, Melosh and Vickery (1989) estimate that the primordial atmosphere on the early Earth could have been reduced in density by a factor of five by such a process. Similar calculations for Mars indicate that atmospheric erosion by impact would be even more severe, with a reduction in density between the primordial atmosphere at 4500 Ma and the atmosphere at about 3500 Ma, by of a factor of about 100. This is due to the small size and low gravity for Mars. In such a scenario, the surface pressure in earliest Martian history would have been closer to 1 bar than the present 0.005–0.01 bar. This may account for the evidence for ancient fluvial activity and enhanced erosion, and their cessation on the surface of Mars during the period of early heavy bombardment (Baker and Partridge, 1986).

Some $5 \times 10^{27}\text{ J}$ is needed to evaporate the present oceans of Earth. Assuming 25 per cent of the impact energy is used in evaporating the oceans, this corresponds to the impact on Earth of a body in the 500 km size range, similar to the present-day asteroids Pallas and Vesta (Sleep and others, 1989). Such an event is possible during the period of early bombardment and would effectively sterilize the surface of the Earth. In such an event, the Earth would have been enveloped by a hot rock vapour atmosphere that would radiate heat downward on to the surface, with an effective temperature of 2000 K. Sleep and others (1989) estimate that it would take 3000 y for the water-saturated atmosphere to rain out and reform the oceans. They estimate that smaller impacts by bodies in the 200 km size range would be sufficient to evaporate the photic zone of the oceans.

Maher and Stevenson (1988) have examined this impact frustration of life from a temporal point of view. They conclude that life could survive in a deep marine setting as early as 4200–4000 Ma. Smaller impacts, however, would continue to make the surface inhospitable until 4000–3700 Ma. Similarly, photosynthesis would have been difficult before 3700 Ma, because of relatively frequent impact-induced climatic excursions.

Impact and later planetary evolution

By 3500 Ma, the cratering rate in the Earth-Moon system had essentially stabilized to something approaching a constant rate (figure 1), which has continued within a factor of two to the present. While major basin-forming impacts were no longer occurring, there were still occasional impacts resulting in craters in the 100 km or greater size range. For example, the terrestrial record contains remnants of the Sudbury, Canada and Vredefort, South Africa structures, which have estimated original crater diameters of 200 km and 140 or possibly 300 km, respectively, and ages of 2000 Ma. Events of this size are unlikely to cause significant long-term changes in the geosphere. In more recent Phanerozoic time, there are a number of large craters preserved on Earth, e.g. Manicouagan, Canada, diameter: 100 km, age: 212 ± 2 Ma (figure 3); Popigai, USSR, diameter: 100 km, age: 35 ± 5 Ma. These are temporally close to transitions in the biostratigraphic record on Earth but this may be coincidental. There is, at present, no direct physical or chemical link between these large-impact events and changes in the biostratigraphic record. Nevertheless, these and other known large-impact events, as well as

many more of similar size, not discovered or unpreserved in the record, must have affected the atmosphere and climate, at least on a local, if not global, scale. The kinetic energies of impact events resulting in craters in the 100 km size range is 10^{21} – 10^{22} J, or 10^6 megatons TNT equivalent, of the same order as the annual output of internal energy of the Earth. Impact events of this size produce associated seismic events of magnitude 10–11.

A considerable, and often confusing, literature now exists over the evidence for a major impact event at the Cretaceous–Tertiary (K/T) boundary and its association with mass extinctions. Benchmark compendia on the subject and related topics can be found in Silver and Schultz (1982) and Sharpton and Ward (1991). The physical evidence for impact contained in K/T boundary deposits consists of shock-produced microscopic planar deformation features in quartz (figure 4), feldspar, zircon and chromite (Bohor and others, 1984, 1987; Izett, 1987); the occurrence of stishovite, the high-pressure polymorph of quartz (McHone and others, 1989); high-temperature magnesioferrite spinels believed to be vapour condensates (Kyte and Smit, 1986); and various spherules, generally altered (Montanari and others, 1983; Smit and Klaver, 1981) but including a recent find of tektite-like glass spherules in Haiti (Sigurdsson and others, 1991). The chemical evidence consists primarily of a siderophile anomaly in the K/T boundary deposits, indicative of an admixture of meteoritic material (Alvarez and others, 1980; Ganapathy, 1980; Kyte and others, 1980).

The original hypothesis by Alvarez and others (1980) for a potential killing mechanism suggested global darkening and cessation of photosynthesis due to ejecta in the atmosphere. Atmospheric evolution models involving dust loadings of 5×10^{18} g, the amount expected from a K/T-sized event, are consistent with this scenario.

They indicate atmospheric residence times of about six months, with optical depths below that required for photosynthesis for some three months and below freezing temperatures on land for around six months (Toon and others, 1982). They also indicate similar effects for dust loadings two orders of magnitude lower (Gerstl and Zardecki, 1982; Toon and others, 1982). Such dust loadings would be achieved in the formation of impact structures in the 50–100 km size range, i.e. corresponding to known Phanerozoic-aged terrestrial impact structures that are not associated with known mass extinctions of the severity of the K/T. One of the assumptions in the model calculations is that the size of the dust particles is equivalent to windblown and volcanic dust, which is of the order of $0.5 \mu\text{m}$ (Toon and others, 1982). The physical evidence from K/T boundary

Figure 3 Landsat image of Manicouagan, the largest known Phanerozoic-aged impact crater in North America. The annular lake is approximately 65 km in diameter and the original rim is estimated to have been 100 km in diameter. Circular drainage to the northwest is due to lithology not a second impact structure.

Figure 4 (a) Photomicrograph of 0.2 mm quartz grain with multiple sets of planar deformation features from the Haughton impact crater, Canada. (b) Photomicrograph of 0.15 mm quartz grain with multiple sets of planar deformation features from K/T boundary deposits, Raton Basin, USA. Compare with Figure 6a.

deposits indicates that the shocked quartz and feldspar grains are in the size range 0.1–0.6 mm (Bohor, 1990), the magnesioferrite crystals range up to 0.04 mm and the altered spherules are in the size range 0.05–1.0 mm, and the partially altered, tektite-like spherules from Haiti range up to 0.6 mm (Sigurdsson and others, 1991). Particles of this size would rain out of the atmosphere very quickly, suggesting that the original 'lights-out' scenario of Alvarez and others (1980) may require modification.

Other potential killing mechanisms have been suggested. They include a period of initial cooling due to dust, followed by global warming, as the result of an oceanic impact and injection of water in the atmosphere, producing an enhanced greenhouse effect and a transient increase in global temperatures of the order of 10°C (Emiliani and others, 1981). Calculations of shock wave heating of the atmosphere during the Tunguska event in 1908 suggest that 3×10^{10} g of nitric oxide may have been formed (Turco and others, 1982). This would lead to depletion of the ozone layer. Observations in the three years following the Tunguska event indicate a 30 ± 15 per cent depletion of ozone. Based on this, Prinn and Fegley (1987) have calculated the shock heating and chemical reprocessing of the Earth's atmosphere due to shock heating during atmospheric entry and by the plume of ejecta in a K/T-sized impact event. Depending on whether the impacting body was a comet or asteroid, they conclude that it would have resulted in global acid rains with pH values rang-

ing from 0 to 5. This would result in the defoliation of plants, the asphyxiation of lung-respiring animals and the killing of calcareous organisms in the top 150 m of the world's oceans. Acid rain would also lead to enhanced chemical erosion of the continents, particularly with respect to the more insoluble metals.

It was models of impact-induced massive global dust loading of the atmosphere and its potential effects on the climate and biosphere that initiated studies of 'nuclear winter' scenarios (Turco and others, 1983). In the latter, however, global darkening as a function of energy release is much more efficient, due to soot and particulate matter from the combustion of natural and man-made materials from the high thermal pulse associated with nuclear explosions. Soot, however, has also been identified in K/T boundary deposits and its origin has been ascribed to global wild-fires (Wolbach and others, 1985). The calculated global abundance of this soot is sufficient to produce optical depths in the atmosphere far below those required for photosynthesis. The soot, therefore, may enhance or even overwhelm the effects produced by global dust clouds. This closes an intellectual loop from the original K/T 'lights-out' scenario due to dust, through scenarios of global darkening due to soot from a man-made 'nuclear-winter' to an indirectly impact-produced soot causing a natural and truly massive 'impact-winter' at the K/T boundary.

During the study of the K/T impact, more and more emphasis has been placed on understanding the effects of the vaporized and melted ejecta from the impact event on the atmosphere. It is this hot expanding vapor cloud that may provide a mechanism for igniting global wild-fires. Models of the thermal radiation produced by the ballistic re-entry of ejecta condensed from the vapour plume of the K/T impact indicate a thermal radiation pulse on the Earth's surface equivalent to some 10 kW m^{-2} for up to several hours (Melosh and others, 1990). This thermal radiation may be directly responsible for global wild-fires; or indirectly responsible, by the global killing and drying of vegetation that is later ignited by lightning strikes. The calculations of Melosh and others (1990) also indicate that the thermal radiation produced by the K/T event is at the lower end of that required to ignite living plant materials. If global wild-fires are a requirement to produce global mass extinction effects, in addition to the deleterious effect of atmospheric dust-loadings and acid rain, then this may explain why impacts that result in 50–100 km-size craters do not result in mass extinctions. They may produce sufficient dust, according to the models, but the accompanying thermal radiation is insufficient to result in the global ignition of living plant materials.

Despite the growing and self-consistent evidence; a sector of the geoscience community continues to argue against the impact interpretation for the K/T boundary (e.g., Officer and Drake, 1989; Loper and McCartney, 1988). While the record in the K/T boundary deposits is consistent with the impact interpretation, it is clear that many of the details are not known at the present time; particularly, with respect to potential killing mechanism and associated mass extinctions. One of the arguments of the opponents of the impact interpretation is that there is no known K/T crater. Without this 'smoking gun', they have argued that the physical and chemical evidence is circumstantial and open to various interpretations (Officer, 1990). As a result, considerable effort has been undertaken to identify the K/T crater or craters in the terrestrial record.

A number of known structures have been suggested as candidates, e.g., Manson, USA (French, 1984), and Kara and Ust-Kara, Russia (Masaitis and Maschak, 1982). The most recent candidate is a 180 km-diameter crater, known as Chicxulub, on the Yucatan peninsula, Mexico (Hildebrand and others, 1991). In this buried structure, evidence for impact, in the form of shock-produced planar deformation features in quartz in deposits interior and exterior to the structure, as well as impact melt rocks, has been reported (Hildebrand and others, 1991; Kring and others, 1991). Variations in the concentration and size of shocked quartz grains and the thickness of K/T boundary deposits (Bohor and others, 1987; Izett, 1987) point towards a source in the Americas. In addition, the geochemistry of K/T tektite glasses from Haiti matches the mixture of

lithologies found at the Chicxulub site (Sigurdsson and others, 1991) and recent isotopic ages for the melt rocks at Chicxulub of 64.98 ± 0.05 Ma are indistinguishable from the K/T tektites at 65.07 ± 1.0 Ma (Swisher and others, 1992). Thus, Chicxulub is by far the most viable candidate for the K/T boundary impact site. A considerable thickness of anhydrite (CaSO_4) occurs in the target rocks at Chicxulub. Impact heating would drive off SO_2 , producing 600 billion tonnes of sulphuric acid aerosol in the atmosphere (Brett, 1992). The effects of SO_2 aerosols on atmospheric cooling is greater than dust particles and ultimately the sulphur will return to earth as sulphuric acid, which would further severely damage the biosphere. It may be that the devastating effects of the K/T impact compared to other known large impacts is due to the unusual composition of the target rocks.

Following the evidence for the K/T impact hypothesis, Raup and Sepkoski (1982, 1986) suggested a periodicity in extinctions in the marine biological record on the basis of time-series analysis. Others applied time-series analysis to the terrestrial cratering record and suggested an equivalent periodicity and, thus, a causal relationship (Alvarez and Muller, 1984; Rampino and Stothers, 1984). This has been extended to other aspects of terrestrial geologic history, including tectonic and volcanic phenomena, and it has been suggested that impact may produce perturbations in mantle convection (Rampino and Stothers, 1985). Given that impact is essentially a surface phenomenon and that no documented evidence exists of impact-induced volcanism, these suggestions must be considered highly speculative. In addition, when actual age uncertainties are taken into account in modelling periodicities in the terrestrial cratering record, it is essentially impossible to define any stable periodicity (Grieve and others, 1988). Model calculations indicate that the period in a 50:50 mix of periodic and random crater ages can be detected for more than 50 per cent of the time, at the 99 per cent confidence level, only if age uncertainties are below 10 per cent of the period being sought. For the 30 Ma period discussed in the literature, this is ± 3 Ma and is unrealistic, given the age uncertainties on terrestrial craters. The statistical arguments concerning uncertainties and the biases in the record notwithstanding, some workers still

consider that there is some merit to the periodicity argument (e.g. Napier, 1989).

At present, the K/T is the only biostratigraphic boundary with a clear signal of the involvement of a large-scale impact event. The involvement of impact in other boundary events in the terrestrial stratigraphic record has been suggested (Xu and others, 1989; McLaren and Goodfellow, 1990) but little definitive chemical or physical evidence has been offered.

The present impact flux as a hazard to humans

At the present time, some 10^5 – 10^6 g of interplanetary debris enters the Earth's atmosphere daily. By many orders of magnitude, the bulk of the extraterrestrial matter is in the form of cosmic dust particles, each with a mass of less than 10^{-9} g. Due to the effects of the atmosphere and high rate of endogenic and geological process on the surface, the Earth retains a poor record of the impact flux. This is true even for larger objects, with the potential to form craterform structures. For example, all known terrestrial craters with diameters ≤ 1 km, and produced by bodies $\leq 10^{11}$ g, were formed by iron or stony iron meteorites, even although these classes of meteorites represent less than 50 per cent of known meteorite falls and finds (Dodd, 1981). The bias towards irons in forming the smaller craters is due to the atmospheric crushing and dispersal of weaker stone meteorites (Melosh, 1981). The effective shielding provided by the Earth's atmosphere, and the resultant reduction in impact velocity by atmospheric retardation of small meteorites, results in the daily background infall of the smallest interplanetary materials being of little hazard to individuals; although structures have been damaged and individuals have been injured. The ultimate effect of atmospheric shielding for the terrestrial planets occurs on Venus. Here, the dense atmosphere (surface pressure 90 times that of the Earth) leads to the breakup of even larger bodies; and craters less than 15 km in diame-

Figure 5 Variations in the relative frequency of impact craters on the lunar surface. Note increase in relative frequency by 30 orders of magnitude in going from 1000 km-sized to submicrometer-sized craters. Vertical axes shows cumulative number of craters equal or larger than a given diameter per unit area. Data from Heiken and others (1990).

ter have irregular, often overlapping shapes, indicative of meteorite breakup and dispersion (Phillips and others, 1991).

A better sample of the interplanetary flux of material in the Earth-Moon system can be gained from the lunar surface. With no atmospheric effects, the impact of all sizes of bodies has been recorded on the lunar surface over geological time. The relative frequency of impacts increases almost 30 orders of magnitude with decreasing size of the impact events, as recorded in lunar craters ranging from a thousand kilometres to less than a micron (figure 5). Impact velocities at the lunar surface are of the order of 13–15 km s⁻¹ (Zook, 1975) and, as there is no atmospheric retardation, relatively small bodies can effect damage. For example, a particle of 10⁻⁶g can produce a 500 µm crater in metal (Vaniman and others, 1991). In brittle materials, there will be an additional zone of fracturing. Following establishment of a future permanent human presence on the lunar surface, the size-frequency distribution of micrometeorites indicates that particles of the order of 10⁻³g are expected to strike large structures and equipment annually. A few millimetres of composite materials, however, would provide an effective shield for such structures against damage from bodies in this size range.

Impacts by larger bodies would be more damaging but would be less frequent (figure 5). For bodies of 1g, i.e. on the scale of the smallest recoverable meteorites on Earth, craters on the centimetre scale would result. Data from microcraters on lunar rocks and measurements by various spacecraft (Grün and others, 1985) indicate that several million such events occur on the lunar surface annually. While an impressive number, the probability of them resulting in injury to an individual astronaut, which represents a relatively small target, is 10⁻⁶ to 10⁻⁸, for a cumulative exposure time of a year (Vaniman and others, 1991). It would appear, therefore, that, like on the Earth, there is little individual risk from the impact of small particles on the lunar surface. Most risk would occur as damage to areally large structures, which are exposed on a continuous basis for many years. In this case, however, it is difficult to assess the actual hazard. Impact on a warehouse structure would be considerably less hazardous than impact in a control system associated with living quarters. In any event, it is likely that such sensitive targets could be adequately protected by design and shielding. Thus, it would appear that, although relatively numerous, the present flux of small bodies are of little hazard to humans, whether on Earth or, in the future, on extended mission in near-Earth orbit and the surface of the Moon.

The terrestrial cratering rate in relatively recent geological time is estimated at $5.4 \pm 2.7 \times 10^{-15}$ km² y⁻¹ for craters with diameters greater than 20 km. Assuming a cumulative frequency distribution of $N \propto D^{-2}$, where N is cumulative number and D is diameter in km, the frequency of K/T-sized events on Earth is of the order of one every 50–100 Ma. Smaller, but still significant impact events, occur on shorter time scales (figure 6). Although such events may not be sufficient to produce mass extinctions, they will affect the terrestrial climate and biosphere to varying degrees. As noted previously, the model calculations of Gerstl and Zardecki (1982) suggest that dust loadings from the formation of impact craters as small as 20 km could produce light reductions and temperature disruptions. Such impacts occur on Earth with a frequency of two or three every million years. The most recent known structure in this size range is Zhamanshin with a diameter of 15 km and an age of 1 Ma. Impacts of this scale are not likely to have a serious affect upon the biosphere. The most fragile component of the present environment, however, is human civilization, which is highly stressed and dependent on an organized and technologically complex infrastructure for its survival. While we seldom think of civilization in terms of million of years, there is little doubt that if civilization lasts long enough it will suffer severely or may even be destroyed by an impact event.

Impact events can occur, however, on human time-scales. For example, the Tunguska event in 1908 was due to the atmospheric explosion of a relatively small—several hundred metres in diameter—body at an altitude of about 10 km. The energy released,

Figure 6 Energy released by largest impact events on Earth over various periods of time from 10⁵ to 10⁸ years. Bars are for the total area of the Earth, with stippled portions representing the energy of the largest event on the land surface. Vertical energy scales are in both Joules and megatons TNT equivalent. Shown for comparison by horizontal lines are the energies of various man-made and natural events. Note that an impact event releasing energy in excess of the world's nuclear arsenal occurs more than once every 10⁶ y on the Earth's land surface.

based on the energy required to produce the observed seismic disturbances, has been estimated to be 10¹⁷–10¹⁸ J, which is 10–100 megatons TNT equivalent. Although the air blast resulted in the devastation of about 2000 km² of Siberian forest (figure 7), there was no loss of human life because of the very sparse population. Events such as Tunguska occur on a time-scale of hundreds of years, and the next Tunguska-sized event may be over an urban centre. The rate at which the human population is expanding makes it all the more likely that loss of life will occur in the next Tunguska-sized event.

While we can take some collective comfort in the fact that civilization-threatening impact events occur only every half million years or so, it must be remembered that impact is a random process not only in space but also in time. The next large impact with the Earth could be a 'impact-winter' producing event or even a K/T-sized event. To emphasize this point, in March 1989 an asteroidal body named 1989 FC passed within 700 000 km of the Earth (Chapman and Morrison, 1990). This Earth-crossing body was not discovered until it had passed the Earth. It is estimated to be in the 0.5 km range, capable of producing a Zhamanshin-sized crater. Although 700 000 km is a considerable distance, it translates to a miss of the Earth by only a few hours, when orbital velocities are considered.

Figure 7 Photograph of the devastation to the Siberian forest 8 km from the ground-zero point of the 1908 Tunguska explosion, resulting from the entry of a small piece of cometary material into the Earth's atmosphere. Such events occur on Earth on time-scales of hundreds of years.

References

- Alvarez, W, and Muller, R A, 1984, Evidence from crater ages for periodic impact on the Earth: *Nature*, London, v. 308, pp. 718–720.
- Alvarez, L W, Alvarez, W, Asaro, F, and Michel, H V, 1980, Extraterrestrial cause for the Cretaceous–Tertiary extinction: *Science*, v. 208, pp. 1095–1108.
- Baker, V R, and Patridge, J B, 1986, Small Martian valleys: pristine and degraded morphology: *Journal of Geophysical Research*, v. 91, pp. 3561–3572.
- Benz, W, Slattery, W L, and Cameron, A G W, 1986, Snapshots from a three-dimensional modelling of a giant impact, in Hartmann, W K, Phillips, R J, and Taylor, G J, eds., *Origin of the Moon*: Houston, Texas, Lunar and Planetary Institute, pp. 617–620.
- Bohor, B F, Foord, E E, Modreski, P J, and Triplehorn, D M, 1984, Mineralogic evidence for an impact event at the Cretaceous–Tertiary boundary: *Science*, v. 224, pp. 867–869.
- Bohor, B F, Modreski, P J, and Foord, E E, 1987, Shocked quartz in the Cretaceous–Tertiary boundary clays: evidence for a global distribution: *Science*, v. 236, pp. 705–709.
- Bratt, S R, Solomon, S C, Head, J W, and Thurber, C H, 1985a, The deep structure of lunar basins: implications for basin formation and modification: *Journal of Geophysical Research*, v. 90, pp. 3049–3064.
- Bratt, S R, Solomon, S C, and Head, J W, 1985b, The evolution on impact basins: cooling, subsidence, and thermal stress: *Journal of Geophysical Research*, v. 90, pp. 12 415–12 433.
- Cameron, A G W, 1983, Origin of the atmospheres of the terrestrial planets: *Icarus*, v. 56, pp. 195–201.
- Cameron, A G W, and Ward, W R, 1976, The origin of the Moon [abs.]: *Lunar and Planetary Science VII*, pp. 120–122.
- Chapman, C R, and Morrison, D, 1989, *Cosmic catastrophes*: New York, New York, Plenum Press.
- Dodd, R T, 1981, *Meteorites*: New York, New York, Cambridge University Press.
- Donhaue, T M, and Pollock, J B, 1983, Origin and evolution of the atmosphere of Venus, in Hunter, D M, Colin, L, Donhaue, T M, and Moroz, V I, eds., *Venus*: Tucson, Arizona, University of Arizona Press, pp. 1003–1036.
- Emiliani, C, Kraus, E B, and Shoemaker, E M, 1981, Sudden death at the end of the Mesozoic: *Earth and Planetary Science Letters*, v. 55, pp. 317–334.
- French, B M, 1984, Impact event at the Cretaceous–Tertiary boundary: a possible site: *Science*, v. 226, p. 353.
- Frey, H, 1980, Crustal evolution of the early Earth: the role of major impacts: *Precambrian Research*, v. 10, pp. 195–216.
- Ganapathy, R, 1980, A major meteorite impact on the Earth 65 million years ago: evidence from the Cretaceous–Tertiary boundary clay: *Science*, v. 209, pp. 921–923.
- Gerstl, S A W, and Zardecki, A, 1982, Reduction of photosynthetically active radiation under extreme stratospheric aerosol loads: *Geological Society of America Special Paper 190*, pp. 201–210.
- Glikson, A Y, 1976, Earliest Precambrian ultramafic-mafic volcanic rocks: ancient oceanic crust of relic terrestrial maria?: *Geology*, v. 4, pp. 201–205.
- Goodwin, A M, 1976, Giant impacting and the development of continental crust, in Windley, B F, ed., *The early history of the Earth*: New York, New York, Wiley, pp. 77–88.
- Green, D H, 1972, Archean greenstone belts may include terrestrial equivalent of lunar maria: *Earth and Planetary Science Letters*, v. 15, pp. 263.
- Grieve, R A F, 1980, Impact bombardment and its role in proto-continental growth on the early Earth: *Precambrian Research*, v. 10, pp. 217–247.
- Grieve, R A F, and Parmentier, E M, 1984, Impact phenomena as factors in the evolution of the Earth: *International Geologic Congress*, 27th, Moscow, v. 19, pp. 99–114.
- Grieve, R A F, Pilkington, M, and Parmentier, E, 1990, Large impact basins and the early Earth [abs.]: *International Workshop on Meteorite Impact on the Early Earth*, Perth, Australia, Lunar and Planetary Institute Contribution No. 746, pp. 18–19.
- Grieve, R A F, Sharpton, V L, Rupert, J D, and Goodacre, A K, 1988, Detecting a periodic signal in the terrestrial cratering record: *Proceedings Lunar and Planetary Science Conference 18th*, pp. 375–382.
- Grün, E, Zook, H A, Fechtig, H, and Geise, R H, 1985, Collisional balance of the meteoritic complex: *Icarus*, v. 62, pp. 244–272.
- Hartmann, W K, 1980, Dropping stones in magma oceans: effects of early lunar cratering, in Merrill, R B, and Papike, J J, eds., *Lunar highlands crust*: New York, New York, Pergamon Press, pp. 155–172.
- Hartmann, W K, and Davis, D R, 1975, Satellite-sized planetismals and lunar origin: *Icarus*, v. 24, pp. 504–515.
- Hartmann, W K, Phillips, R J, and Taylor, G J, eds., 1986, *Origin of the Moon*: Houston, Texas, Lunar and Planetary Institute.
- Head, J W, 1974, Orientale multi-ringed basin interior and implications for the petrogenesis of lunar highland samples: *The Moon*, v. 11, pp. 327–356.
- Head, J W, and Solomon, S C, 1981, Tectonic evolution of the terrestrial planets: *Science*, v. 213, pp. 62–76.
- Heiken, G H, Vaniman, D T, and French, B M, eds., 1990, *Lunar Sourcebook*: New York, Cambridge University Press.
- Hildebrand, A R, Penfield, G T, Kring, D A, Pilkington, M, Camargo, Z A, Jacobsen, S A, and Boynton, W V, 1991, Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico: *Geology*, v. 19, pp. 867–871.
- Hörz, F, Gibbons, R V, Hill, R E, and Gault, D E, 1976, Large scale cratering of the lunar highlands: some Monte Carlo model considerations: *Proceedings Lunar Science Conference 7th*, pp. 2931–2945.
- Howard, K A, Wilhelms, D E, and Scott, D H, 1974, Lunar basin formation and highland stratigraphy: *Reviews of Geophysics and Space Physics*, v. 12, pp. 309–327.
- Izett, G A, 1987, The Cretaceous–Tertiary (K–T) boundary interval, Raton Basin, Colorado and New Mexico, and its content of shock-metamorphosed minerals: implications concerning the K–T boundary impact-extinction theory: *United States Geological Survey Open-File Report 87-606*, pp. 1–125.
- Kipp, M E, and Melosh, H J, 1986, A preliminary numerical study of colliding planets, in Hartmann, W K, Phillips, R J, and Taylor, G J, eds., *Origin of the Moon*: Houston, Texas, Lunar and Planetary Institute, pp. 643–648.
- Kring, D A, Hildebrand, A R, and Boynton, W V, 1991, The petrology of an andesitic melt rock and a polymict breccia from the interior of the Chicxulub structure, Yucatan, Mexico [abs.]: *Lunar and Planetary Science XXII*, pp. 755–756.
- Kyte, F T, and Smit, J, 1986, Regional variations in spinel compositions: an important key to the Cretaceous/Tertiary event: *Geology*, v. 14, pp. 485–487.
- Kyte, F T, Zhou, Z, and Wasson, J T, 1980, Siderophile-enriched sediments from the Cretaceous–Tertiary boundary: *Nature*, London, v. 288, pp. 651–656.
- Lange, M A, and Ahrens, T J, 1979, Impact melting early in lunar history: *Proceedings Lunar and Planetary Science Conference 10th*, pp. 2707–2725.
- Loper, D E, and McCartney, K, 1988, Catastrophic volcanism as a cause of iridium and shocked quartz found at the K/T boundary: *EOS*, v. 16, p. 302.
- Lowman, P D, Jr, 1976, Crustal evolution in silicate planets: implications for the origin of continents: *Journal of Geology*, v. 84, pp. 1–26.
- Maher, K A, and Stevenson, D J, 1988, Impact frustration of the origin of life: *Nature*, London, v. 331, pp. 612–614.

- Masaitis, V L, and Mashchak, M S, 1982, Impact events at the Cretaceous–Paleogene boundary (in Russian): *Doklady Akademii Nauk SSSR*, v. 265, pp. 1500–1503.
- McHone, J F, Nieman, R A, Lewis, C F, and Yates, A M, 1989, Stishovite at the Cretaceous–Tertiary boundary, Raton, New Mexico: *Science*, v. 243, pp. 1182–1184.
- McLaren, D J, and Goodfellow, W D, 1990, Geological and biological consequences of giant impacts: *Annual Review Earth Planetary Science*, v. 18, pp. 123–171.
- Melosh, H J, 1981, Atmospheric breakup of terrestrial impactors, in Schultz, P H, and Merrill, P B, eds., *Multi-ring basins*: New York, New York, Pergamon Press, pp. 29–35.
- Melosh, H J, Schneider, N M, Zahnle, K J, and Latham, D, 1990, Ignition of global wildfires at the Cretaceous/Tertiary boundary: *Nature*, London, v. 343, pp. 251–254.
- Melosh, H J, and Vickery, A M, 1989, Impact erosion of the primordial atmosphere of Mars: *Nature*, London, v. 338, pp. 487–489.
- Montanari, A, Hay, R L, Alvarez, W, Asaro, F, Michel, H V, and Alvarez, L W, 1983, Spheroids at the Cretaceous–Tertiary boundary are altered impact droplets of basaltic composition: *Geology*, v. 11, pp. 668–671.
- Napier, W M, 1989, Terrestrial catastrophism and galactic cycles, in Clube, S V M, ed, *Catastrophes and evolution*: Cambridge, England, Cambridge University Press, pp. 133–168.
- Neukum, G, 1977, Different ages of lunar light plains: *Moon*, v. 17, pp. 383–393.
- Officer, C B, 1990, Extinctions, iridium, and shocked minerals associated with the Cretaceous/Tertiary transition: *Journal of Geological Education*, v. 38, pp. 402–425.
- Officer, C B, and Drake, C L, 1989, Cretaceous/Tertiary extinctions: we know the answer, but what is the question?: *EOS*, v. 70, pp. 659–661.
- Ohtsuki, K, Nakagawa, Y, and Nakazawa, K, 1988, Growth of Earth in nebular gas: *Icarus*, v. 75, pp. 552–565.
- Pepin, R, and Phinney, D, 1975, The formation interval of the Earth [abs.]: *Lunar and Planetary Science VII*, pp. 682–684.
- Phillips, R J, Schaber, G G, Arvidson, R E, Boyce, J M, Campbell, D B, Guest, J E, and Soderblom, L A, 1991, Impact craters on Venus: initial analysis from Magellan: *Science*, v. 252, pp. 288–296.
- Prinn, R G, and Fegley, B, Jr, 1987, Bolidic impacts, acid rain, and biospheric traumas at the Cretaceous–Tertiary boundary: *Earth and Planetary Science Letters*, v. 83, pp. 1–15.
- Rampino, M R, and Stothers, R B, 1984, Geological rhythms and cometary impacts: *Science*, v. 226, pp. 1427–1431.
- Rampino, M R, and Stothers, R B, 1985, Geological periodicities and the galaxy, in Smoluchowski, R, Bahcall, J N, and Matthews, M S, eds., *The Galaxy and the Solar System*: Tucson, Arizona, University of Arizona, pp. 1–38.
- Raup, D M, and Sepkoski, J J, Jr, 1982, Mass extinctions in the marine fossil record: *Science*, v. 215, pp. 1501–1502.
- Raup, D M, and Sepkoski, J J, Jr, 1986, Periodic extinctions of families and genera: *Science*, v. 231, pp. 833–836.
- Ryder, G, 1981, Distribution of rocks at the Apollo 16 landing site, in James, O B, and Hörz, F, eds., *Workshop on Apollo 16*: Houston, Texas, Lunar and Planetary Institute Technical Report 81-01, pp. 112–119.
- Safronov, V S, 1969, Evolution of the protoplanetary cloud and formation of the Earth and Planets (in Russian): *Nauka*, Moscow, 244 p, NASA Technical Translation F-677 (1972).
- Schultz, P H, and Gault, D E, 1975, Seismic effects of major basin formations on the Moon and Mercury: *The Moon*, v. 12, pp. 159–177.
- Sharpton, V L, and Ward, P D, eds., *Global catastrophes in Earth history: an interdisciplinary conference on impacts, volcanism and mass mortality*: Geological Society of America Special Paper 247.
- Sigurdsson, H, D'Hondt, S, Arthur, M A, Bralower, T J, Zachos, J C, van Fossen, M, and Channell, J E T, 1991, Glass from the Cretaceous/Tertiary boundary in Haiti: *Nature*, London, v. 349, pp. 482–487.
- Silver, L T, and Schultz, P H, eds., 1982, Geological implications of impacts of large asteroids and comets on the Earth: *Geological Society of America Special Paper* 190.
- Sleep, N H, Zahnle, K J, Kasting, J F, and Morowitz, H J, 1989, Annihilation of ecosystems by large asteroid impacts on the early Earth: *Nature*, London, v. 342, pp. 139–142.
- Smit, J, and Klaver, G, 1981, Sanidine spherules at the Cretaceous–Tertiary boundary indicate a large impact event: *Nature*, London, v. 292, pp. 47–49.
- Smith, B A, Soderblom, L A, Becke, R, Bliss, D, Boyce, J M, Brahic, A, Briggs, G A, Brown, R H, Collins, S A, Cook, A F, Croft, S K, Cuzzi, J N, Danielson, G E, Davies, M E, Dowling, T E, Godfrey, D, Hansen, C J, Harris, C, Hunt, G E, Ingersoll, A P, Johnson, T V, Krauss, R J, Masursky, H, Morrison, D, Owen, T, Plescia, J B, Pollock, J B, Porco, C C, Rages, K, Sagan, C, Shoemaker, E M, Stromovsky, A, Stroker, C, Strom, R G, Suomi, V E, Synnott, S P, Terile, R J, Thomas, P, Thompson, W R, and Veverka, J, 1986, Voyager 2 in the Uranium system: imaging science results: *Science*, v. 233, pp. 43–64.
- Swisher III, C C, Grajales-Nishimura, J M, Montanari, A, Margolis, S V, Claeys, P, Alvarez, W, Renne, P, Cedillo-Pardo, E, Maurrasse, F J -M R, Curtis, G H, Smit, J, and McWilliams, O, 1992, Coeval $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65.0 million years ago from Chicxulub crater melt rock and Cretaceous–Tertiary boundary tektites: *Science*, v. 257, pp. 954–958.
- Taylor, G J, Warren, P, Ryder, G, Delano, J, Pieters, C, and Lofgren, G, 1991, Lunar rocks, in Heiken, G H, Vaniman, D T, and French, B M, eds., *The lunar source book*: New York, New York, Cambridge University Press, pp. 183–284.
- Toksöz, M N, Dainty, A M, Solomon, S C, and Anderson, K R, 1973, Velocity structure and evolution of the Moon: *Proceedings Lunar Science Conference 4th*, pp. 2529–2547.
- Toon, O B, Pollack, J B, Ackerman, T P, Turco, R P, McKay, C P, and Liu, M S, 1982, Evolution of an impact-generated dust cloud and its effects on the atmosphere: *The Geological Society of America Special Paper* 190, pp. 187–200.
- Turco, R P, Toon, O B, Park, C, Whitten, R C, Pollack, J B, and Noerdlinger, P, 1982, An analysis of the physical, chemical, optical, and historical impacts of the 1908 Tunguska meteor fall: *Icarus*, v. 50, pp. 1–52.
- Turco, R P, Toon, O B, Ackerman, T P, Pollack, J B, and Sagan, C, 1983, Nuclear winter: global consequences of multiple nuclear explosions: *Science*, v. 222, pp. 1283–1292.
- Vaniman, D, Reddy, R, Heiken, G, Olhoeft, G, and Mendell, W, 1991, The lunar environment, in Heiken, G H, Vaniman, D T, and French, B M, eds., *The lunar source book*: New York, New York, Cambridge University Press, pp. 27–60.
- Weiblen, P W, and Schultz, K J, 1978, Is there any record of meteorite impact in the Archean rocks of North America?: *Proceedings Lunar and Planetary Science Conference 9th*, pp. 2749–2773.
- Wetherill, G W, 1985, Occurrence of giant impacts during the growth of the terrestrial planets: *Science*, v. 228, pp. 877–879.
- Wetherill, G W, and Stewart, G R, 1989, Accumulation of a swarm of small planetisms: *Icarus*, v. 77, pp. 330–357.
- Wilhelms, D E, 1987, The geologic history of the Moon: *United States Geological Survey Professional Paper* 1348, p. 302.
- Wolbach, W S, Lewis, R S, and Anders, E, 1985, Cretaceous extinctions: evidence for wildfires and search for meteoritic material: *Science*, v. 230, pp. 167–170.
- Wood, J W, 1986, Moon over Mauna Loa: A review of hypotheses of formation of Earth's Moon, in Hartmann, W K, Phillips, R J, and Taylor, G J, eds., *Origin of the Moon*: Houston, Texas, Lunar and Planetary Institute, pp. 17–56.
- Xu, D -Y, Sun, Y -Y, Zhang, Q -W, Yan, Z, He, J -W, and Chai, Z -F, 1989, Astrogeological events in China: New York, New York, Van Nostrand Reinhold.
- Zook, H A, 1975, The state of meteoritic material on the Moon: *Proceedings Lunar Science Conference 6th*, pp. 1653–1672. □

Richard A F Grieve is a senior research scientist with the Geological Survey of Canada and Vice Chairman of the IUGS Commission on Comparative Planetology. He became interested in comparative planetology while a co-investigator in the Apollo sample analysis program in the early seventies. This led him into the study of the effects of impact on the nature and evolution of planetary surfaces. He is particularly interested in the use of observations at terrestrial impact structures to constrain the understanding of impact processes.