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ASTEROID AND COMET BOMBARDMENT OF THE EARTH[1]

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INTRODUCTION

Two classes of solid bodies large enough to be detected by telescopes occur in orbits that overlap that of the Earth. These bodies are the Earth-crossing asteroids and comet nuclei. Although their orbits only rarely intersect the Earth's, the probabilities of their collision with the Earth are nevertheless finite and calculable. Systematic telescopic surveys carried out over the past two decades show that the flux of asteroids and comet nuclei in the Earth's neighborhood is sufficiently high that the effects of occasional collisions should be recognizable in the geological record. During these same two decades, an intensive international search for ancient impact structures has gone forward. The actual rate of bombardment of the Earth during the last half-billion years has been found to be roughly consistent with the present rate predicted from astronomical observations. Within a factor of about two, the average rate of bombardment of the Earth during the last half-billion years also appears to be consistent with the average rate of bombardment of the Moon over the last 3.3 billion years.

Spectacular new lines of study have developed in recent years leading to the recognition of rare large impact events that produce geochemical anomalies on a global scale. The possible effects of these large impacts on the Earth's biota have become the subject of vigorous debate. In this paper, I first review the astronomical and geologic evidence concerning the history of bombardment and then discuss the physical effects of large impacts, as they may apply to both the inorganic and organic worlds.

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POPULATIONS OF EARTH-CROSSING BODIES

Earth-Crossing Asteroids

The term Earth-crossing asteroid is used here to designate a body of asteroidal appearance at the telescope whose orbit occasionally intersects the orbit of the Earth as a result of distant perturbations by the planets. Such intersections are possible under the condition that the perihelion (point nearest the sun) on the asteroid's orbit lies closer to the sun than the aphelion (point farthest from the sun) on the Earth's orbit. Under this condition, if the asteroid's perihelion were aligned on the same side of the sun with the Earth's aphelion and if the two orbits were coplanar, the orbits would overlap and there would be two points of intersection. In general, the major axes of the two orbits are not so aligned and the orbits are not coplanar. However, distant planetary perturbations cause the major axes of both the asteroid's orbit and the Earth's orbit to precess. During precession, the radius vectors from the sun to the nodes of the asteroid's orbit (the two points on the orbit that lie on the line of intersection of the asteroid's orbit with the Earth's orbit) oscillate between the asteroid's perihelion distance and aphelion distance. If there is continuous overlap of the two orbits, there will be four angles at which the two orbits *must* intersect during a 360° rotation of the major axis of the asteroid's orbit relative to the line of the nodes. If overlap is lost during part of the precession cycle there may be fewer or, in some cases, no intersections.

Distant planetary perturbations also cause secular changes in the eccentricity of both the Earth's orbit and the asteroid's orbit. Hence, the degree of orbital overlap varies as a result of variation in the orbital eccentricities as well as a result of precession. As a consequence, asteroid orbits that now overlap the Earth's orbit can lose overlap, and conversely, there are asteroids whose orbits are not now overlapping that are Earth crossers. In some cases, the combined effects of precession and secular variation of eccentricity lead to 8 or more intersections with the Earth's orbit in a complete cycle of rotation of the major axis of the asteroid's orbit. A semianalytical theory for accurate calculation of the secular perturbations of Earth-crossing asteroid orbits has been developed only in the last 15 years (Williams 1969), and its general application to Earth crossers has been carried out only in the last 5 years (Williams 1979, Shoemaker et al 1979).

The first Earth-crossing asteroid to be discovered was 887 Alinda, a moderately bright ~5 km diameter body found by M. Wolf at Heidelberg, Germany, in 1918. Its present perihelion distance is 1.15 astronomical units (AU); it was not recognized as an Earth crosser until a study of its orbital dynamics was carried out by Marsden (1970). The second Earth crosser to be discovered was 1221 Amor, found by E. Delporte at Uccle, Belgium, in 1932. This tiny body, about 1 km in diameter, has a perihelion distance of 1.08 AU and was not recognized as an Earth crosser until studied by Williams (1979). Asteroids that approach the Earth but whose orbits currently do not overlap the Earth's are now generally referred to as Amor asteroids. About half the known Amor asteroids, with perihelion distances ⩽1.3 AU, have been found to be Earth crossers, chiefly by application of William's secular-perturbation theory. Another asteroid found in 1932, this time by K. Reinmuth at Heidelberg, has an orbit that strongly overlaps the orbit of the Earth. This asteroid is 1862 Apollo, and its name is applied to the class of asteroids with orbits larger than Earth's and with current perihelion distances ⩽1.017 AU (the Earth's aphelion distance). In 1976, asteroid 2062 Aten was discovered by E. F. Helin at Palomar Mountain, California; this object is on an orbit smaller than Earth's, but it overlaps Earth's orbit at aphelion. Three more asteroids have since been recognized that belong to the Aten class.

A total of 49 Earth-crossing asteroids, comprising 4 Atens, 30 Apollos, and 15 Earth-crossing Amors, have been discovered through mid-1982 (Table 1). During the past decade, the average rate of discovery has been about 3 per year. Most of the Earth crossers are so small and intrinsically faint that they are only discovered when near the Earth. The absolute visual magnitude of 35 of the known Earth crossers is equal to or brighter than 18 (Table 1). On the basis of the discovery rate in various systematic surveys of the sky, the population of Earth crossers to absolute visual magnitude 18 is estimated at ~1300, including ~100 Atens, 700±300 Apollos, and ~500 Earth-crossing Amors (Helin & Shoemaker 1979, Shoemaker et al 1979). Hence, the discovery of Earth-crossing asteroids to absolute visual magnitude 18 is estimated to be only 2 to 3% complete as of mid-1982. The impending launch of the Infrared Astronomical Satellite and the construction of a telescope at the Steward Observatory, Arizona, specially designed for the search for Earth-approaching asteroids may greatly accelerate their discovery in the next few years, however.

As they are observed merely as points of light at the telescope, our information about the sizes and other characteristics of Earth-crossing asteroids is derived entirely from analysis of the radiation reflected and emitted from them. Albedos of the asteroids can be determined from the ratio of reflected sunlight to emitted thermal radiation (Morrison 1977, Morrison & Lebofsky 1979). Cross-sectional areas and mean diameters can then be obtained from the absolute magnitudes. Albedos can also be estimated from measurements of polarization of the reflected sunlight (Zellner et al 1974, Dollfus & Zellner 1979) and from the dependence of apparent magnitude upon the angle between the vectors from the asteroid to the Earth and to the sun (Bowell & Lumme 1979).

When determinations of albedo are combined with broad- or narrow-band measurements of color in the visible and near-infrared parts of the spectrum, the asteroids can be classified into several broad groups or types (Bowell et al 1978, Zellner 1979). Asteroids designated *C-type* have visual geometric albedos in the range 0.02 to 0.065 and relatively neutral colors in the visible and near infrared; *S-type* asteroids have geometric albedos in the range 0.065 to 0.23 and reddish colors. Narrow-band spectrophotometry permits comparison of the reflectance spectra of the asteroids with meteorites. Moreover, the absorption bands of discrete mineral phases commonly can be recognized in the near-infrared (Gaffey & McCord 1979). C-type asteroids are generally believed to be compositionally similar to carbonaceous meteorites, whereas S-type asteroids are thought to be somewhat similar to ordinary chondritic meteorites, although only a few good matches of spectral reflectance are found between S-asteroids and ordinary chondrites. The majority of well-observed Earth crossers appear to be referable to the C or S types, but a significant proportion are found to have unusual colors and are not definitely assignable to any major spectrophotometric type (Shoemaker et al 1979).

At absolute visual magnitude 18, C-type asteroids have diameters in the range 1.3 to 2.3 km, and S-type in the range 0.7 to 1.3 km. Most of the Earth crossers observed by means of photoelectric photometry are S-type or have colors that probably are correlated with moderately high albedo, but the bulk of the volume for the observed objects is probably contained in a smaller number of low-albedo, relatively large, C-type objects (Shoemaker et al 1979). Because they are very faint and difficult to observe by photoelectric photometry, small C-type Earth crossers almost certainly are underrepresented in the present statistics.

The probability of collision with the Earth for a body whose orbit strongly overlaps Earth's can be calculated by methods first derived by Öpik (1951) and further developed by Wetherill (1967, 1968) and Shoemaker et al (1979). For orbits with shallow overlap or which overlap only part of the time, use must be made of Williams's (1969) perturbation theory, or of extensive numerical integration of the orbits to obtain the terms required to calculate the collision probability. The mean probability of collision with the Earth for Earth-crossing asteroids was found by Shoemaker et al (1979) to be $\sim 2.5 \times 10^{-9}$ yr^{-1}. When multiplied by the estimated population, this yields a collision rate of about 3.2 per million years for asteroids brighter than absolute magnitude 18. The impact speed may also be obtained from the terms used in the calculation of impact probability. The rms impact speed of Earth-crossing asteroids, weighted

Table 1 Earth-crossing asteroids discovered through May, 1982

Number	Name	Class	a^a (AU)	e^a	i^a (deg.)	q (AU)	Q (AU)	$V(1,0)$	Diameter (km)	References
1566	Icarus	Apollo	1.08	0.827	23.0	0.19	1.97	16.8	1.4	1
2212	Hephaistos	Apollo	2.16	0.835	11.9	0.36	3.97	14.4	(8.7)	2
	1974 MA	Apollo	1.78	0.762	37.8	0.42	3.13	14.2	~6	2
2101	Adonis	Apollo	1.87	0.764	1.4	0.44	3.30	18.8	~1	2
2340	Hathor	Aten	0.84	0.450	5.9	0.46	1.22	20.7	(0.2)	3
2100	Ra-Shalom	Aten	0.83	0.437	15.8	0.47	1.20	16.4	3.4	4
	1954 XA	Aten	0.78	0.345	3.9	0.51	1.05	19.2	~0.6	2
1864	Daedalus	Apollo	1.46	0.615	22.1	0.56	2.36	15.1	(3.3)	5
1865	Cerberus	Apollo	1.08	0.467	16.1	0.58	1.58	16.7	~2	2
	Hermes (1937 UB)	Apollo	1.64	0.624	6.2	0.62	2.66	17.3	~1	2
1981	Midas	Apollo	1.78	0.650	39.8	0.62	2.93	17.2	~2	2
	1981 VA	Apollo	2.46	0.744	22.0	0.63	4.29	17	~2	2
2201	1947 XC	Apollo	2.17	0.712	2.5	0.63	3.72	15.9	~3	2
1862	Apollo	Apollo	1.47	0.560	6.4	0.65	2.29	16.2	1.4	6
	1979 XB	Apollo	2.26	0.713	24.9	0.65	3.88	19.2	~0.6	2
2063	Bacchus	Apollo	1.08	0.349	9.4	0.70	1.45	17.9	~1	2
1685	Toro	Apollo	1.37	0.436	9.4	0.77	1.96	14.2	4.7^b 3.8^c	3 7
2062	Aten	Aten	0.97	0.182	18.9	0.79	1.14	17.6	0.9	8
2135	Aristaeus	Apollo	1.60	0.503	23.0	0.79	2.40	18.4	~1	2
	1982 HR	Apollo	1.21	0.332	2.7	0.82	1.60	19	~0.5	
2329	Orthos	Apollo	2.40	0.658	24.4	0.82	3.99	15.5	~3	2
	6743P-L	Apollo	1.62	0.493	7.3	0.82	2.42	17.6	~1	2
1620	Geographos	Apollo	1.24	0.335	13.3	0.83	1.66	15.9	2.0	1
	1959 LM	Apollo	1.34	0.379	3.3	0.83	1.85	15.2	~3	2
	1950 DA	Apollo	1.68	0.502	12.1	0.84	2.53	16.1	~3	2

Table 1 (*continued*)

Number	Name	Class	a^a (AU)	e^a	i^a (deg.)	q (AU)	Q (AU)	$V(1,0)$	Diameter (km)	References
1866	Sisyphus	Apollo[d]	1.89	0.540	41.1	0.87	2.92	13.8	~10	2
	1973 NA	Apollo	2.46	0.642	68.1	0.88	4.04	15.3	~6	2
	1978 CA	Apollo	1.12	0.215	26.1	0.88	1.37	18.1	1.9	4
1863	Antinous	Apollo	2.26	0.606	18.4	0.89	3.63	15.7	~3	2
	1982 BB	Apollo	1.41	0.355	21.0	0.91	1.91	15	~4	
2102	Tantalus	Apollo	1.29	0.298	64.0	0.91	1.67	16.7	~3	2
	6344P-L	Apollo	2.58	0.635	4.6	0.94	4.21	22.3	~0.2	2
	1982 DB	Apollo	1.48	0.356	1.4	0.95	2.01	19	~1	
	1979 VA	Apollo	2.64	0.627	2.8	0.98	4.29	16.6	(3.2)	2
	1978 DA	Amor	2.48	0.587	15.6	1.02	3.93	18.0	0.9	4
	1980 PA	Amor	1.93	0.459	2.2	1.04	2.81	18.7	~1	2
2061	Anza	Amor	2.26	0.537	3.7	1.05	3.48	17.3	(2.3)	2
1915	Quetzalcoatl	Amor	2.52	0.583	20.5	1.05	3.99	18.6	0.4	7
	1980 AA	Amor	1.89	0.444	4.2	1.05	2.73	19.7	~0.5	2
1917	Cuyo	Amor	2.15	0.505	24.0	1.06	3.23	15.7	~3	2
1943	Anteros	Amor	1.43	0.256	8.7	1.06	1.80	15.7	2.0	7
	1981 QB	Amor	2.24	0.519	37.2	1.08	3.40	16	~3	2
1221	Amor	Amor	1.92	0.436	11.9	1.08	2.76	18.3	~1	2
	1980 WF	Amor	2.23	0.514	6.4	1.08	3.38	18.7	~1	2
	1982 DV	Amor	2.03	0.457	5.9	1.10	2.96	16	~3	
1580	Betulia	Amor	2.20	0.490	52.0	1.12	3.27	14.3	7.4	9
2202	Pele	Amor	2.29	0.510	8.8	1.12	3.46	17.7	~1	2
1627	Ivar	Amor	1.86	0.397	8.4	1.12	2.60	13.4	6.2	7
887	Alinda	Amor	2.52	0.544	9.1	1.15	3.88	14.1	4.7	3

Explanation of headings:

Number A permanent number is assigned to an Earth-crossing asteroid after its positions have been measured on two appearances near opposition (the direction opposite from the sun) and an accurate orbit has been determined.

Name For asteroids that have been assigned a permanent number, a name is proposed by the discoverer and adopted under the rules of the International Astronomical Union. At the time of discovery, a provisional designation is assigned (e.g. 1974 MA) which indicates the year (1974), half month (M), and sequence within the half month (A) in which the asteroid was reported to the Minor Planet Center. This designation is used until the asteroid is numbered, except for Hermes, which was named in violation of the rules. Asteroids discovered in the Palomar-Leiden survey for faint minor planets (van Houten et al 1970) received a special provisional designation, indicated by the suffix P-L.

Class Orbital class, generally named for the first member recognized (see text).

a Semimajor axis of orbit in astronomical units. The astronomical unit (AU) is the length of the semimajor axis of the Earth's orbit.

e Eccentricity of orbit.

i Inclination of orbit.

q Perihelion distance in astronomical units.

Q Aphelion distance in astronomical units.

$V(1,0)$ Absolute visual magnitude (mean magnitude as observed through a yellow filter and reduced to 1 AU distance from the Earth, 1 AU distance from the sun, and a position directly opposite from the sun). An increase of one magnitude corresponds to a decrease in brightness by a factor of $(100)^{1/5}$. Magnitudes for numbered asteroids are chiefly from Bowell et al (1979).

Diameter Diameter of a circular area equivalent to the mean cross-sectional area of the asteroid. Diameters based on measured albedos are reported to one decimal place without parentheses; diameters based on albedos inferred from broad-band color ratios are shown in parentheses; diameters based on albedos assumed without any photometric evidence are shown as approximate values.

References Index number for reference or source from which diameters are taken, as follows: 1. Zellner et al 1974; 2. Wetherill & Shoemaker 1982; 3. Bowell et al 1979; 4. Lebofsky et al 1979; 5. Bowell et al 1978; 6. Lebofsky et al 1981; 7. G. J. Veeder, personal communication, 1982; 8. Morrison et al 1976; 9. Lebofsky et al 1978.

Footnotes

[a] Orbital elements are from Ephemerides of Minor Planets (Akademia Nauk) and the Minor Planet Circulars.

[b] Diameter based on determination of albedo by polarimetry.

[c] Diameter based on determination of albedo by infrared radiometry.

[d] The orbit of Sisyphus generally does not intersect Earth's orbit during precession of the axis of the asteroid's orbit, owing to change of e and loss of overlap of the orbits.

according to probability of collision, was found to be 20.1 km s^{-1} (Shoemaker et al 1979).

The Earth-crossing asteroid swarm is depleted by collision with the Earth and with the other planets and by ejection of asteroids from the solar system as a result of successive close encounters with the planets. Typical dynamical lifetimes for these bodies are only about 3×10^7 yr (Wetherill & Williams 1968, Wetherill 1976). The swarm would be quickly diminished if the losses were not balanced by injection of new asteroids into Earth-crossing orbits. Rough consistency between the present estimated cratering rate and the geologic record of impact back to ~0.5 Gyr suggests that the population of Earth crossers is approximately in equilibrium. Analysis of the lunar-cratering record, however, suggests that the average flux of impacting bodies during the last half-billion years may have been about twice as high as the average flux over the past 3.3 Gyr (Shoemaker et al 1979). Some Earth-crossing asteroids are certainly derived from the main asteroid belt and are injected into Earth-crossing orbits by a combination of the effects of dynamical resonances and close encounters with Mars (Wetherill 1979). Others may be extinct, very short period comets (Öpik 1963, Marsden 1971, Sekanina 1971, Wetherill 1976, Degewij & Tedesco 1982). If a residue or core of rocky material is left when all the ices have sublimed from a comet like P/Encke, which is on an orbit like that of some Earth-crossing asteroids, the object would be recognized at the telescope as an Earth-crossing asteroid. Coarse rocky material may also form a lag deposit on the surface of an ablating comet nucleus, which might shut off observable cometary activity and thus produce an asteroid. If only about one in ten to a hundred comets like P/Encke evolve into objects of asteroidal appearance, the supply would appear to be adequate to maintain the Earth-crossing asteroid population (cf Wetherill 1979, Shoemaker et al 1979).

Comets

More than 10^{12} comet nuclei are estimated to reside in a spherical cloud, over a light year in diameter, that surrounds the sun (Weissman 1982a). Repeated perturbation of this distant cloud of comets by passing stars produces a small, but fairly steady, flux of comets in the region of the planets (Oort 1950, Weissman 1980). Most comets arrive in the Earth's neighborhood on extremely eccentric orbits, with periods ranging from thousands to millions of years; a substantial fraction of these are perturbed by the gravitational attraction of the giant planets into trajectories that allow them to escape from the solar system. Successive perturbations by the giant planets also lead to capture of about 0.01% of the long-period comets into orbits with periods less than 20 years. More than 500 long-period comets have been observed over the past few centuries, most of which passed inside the orbit of the Earth (Marsden 1979); somewhat more than 100 comets with periods $\leqslant 20$ years have also been discovered (Marsden 1979), but only a minor fraction of these cross the Earth's orbit.

Our information about the physical characteristics of comet nuclei is derived chiefly from observation of the gases and entrained dust that are liberated as the comets approach the sun. The nuclei are rotating solid bodies (Sekanina 1981, Whipple 1982), evidently composed chiefly of H_2O ice and embedded rocky particles (Whipple 1950, 1951, Delsemme 1982). An extended dusty atmosphere produced by insolation generally obscures the nucleus of the comet when it is close enough to the Earth for detailed photometric and radiometric observation. For this reason, present estimates of the sizes of comet nuclei are very uncertain. Observations of the amounts of gas and dust released, the acceleration of the comets by the jet effect of the released material (Whipple 1978), and photometric observations of comet nuclei when they are distant from the sun (Roemer 1966) suggest that the nuclei range in diameter from less than one kilometer to several tens of kilometers. Detection of P/Encke by radar indicates that the diameter of the nucleus of this comet is in the range of ~0.4 to 4.0 km (Kamoun et al 1981). Shoemaker (1981) and Shoemaker & Wolfe (1982) estimate that impacts of comet nuclei, dominantly on long-period orbits, may account for as much as ~30% of the recent production of impact craters larger than 10 km diameter on Earth. Weissman (1982b), on the other hand, estimates the cratering rate by comet impact at only ~10% of the total rate. This disagreement is due chiefly to differences in the evaluation of sizes of the long-period comet nuclei.

PRODUCTION OF IMPACT CRATERS ON THE CONTINENTS

Crater Scaling

If a colliding body is sufficiently large, the most easily recognized effect of its encounter with the Earth generally is an impact crater. The size of the crater produced depends primarily upon the mass, density, shock compressibility, and velocity of the impacting body, and upon the density, shock equation of state, and strength of the target rocks. The functional relationship between these variables and the size and shape of the crater has been the subject of fairly intensive theoretical and experimental investigation for the last two decades (Roddy et al 1977, Melosh 1980).

Impact cratering is such a sufficiently complicated process that we cannot yet predict with high accuracy and confidence the consequences of impact on land of the Earth-crossing bodies discovered at the telescope. The most reliable predictions, at present, are obtained from the use of state-of-the-art, large, finite difference computer codes, in which the model includes all of the above variables and whatever stratification or structure of the target may be appropriate. The target and the projectile are divided into a large number of cells in a rectangular array, and the history of a specific impact event is carried forward in small increments of time for each cell on the basis of the physics of the propagation of the shock and rarefaction waves generated by the impact. Even with the use of special very high speed computers, the calculation of a single case of impact is time-consuming and expensive. To simplify the calculation and reduce the expense, generally only cases of symmetrical projectiles impacting at vertical incidence have been investigated.

A number of code calculations, for the most part with progressively greater sophistication, have been run to simulate the impact event that produced Meteor Crater, Arizona. In this case, the properties of the meteorite and the target rocks, the structure of the target, and the resulting crater and associated structural deformation are all well known, but the mass, shape, and velocity of the projectile are unknown. Among the calculations published to date, one carried out by Roddy et al (1980) employs the most advanced code. The degree to which this code adequately represents the physical processes in cratering has been checked by numerous calculations of large explosion craters and comparison of the results with highly instrumental field experiments.

For impact of a single projectile at vertical incidence, Roddy et al (1980) estimate that the kinetic energy of the meteorite required to form Meteor Crater was ~15 megatons TNT equivalent. (One megaton TNT is equivalent to 4.19×10^{22} ergs.) Their calculations suggest that the volume of craters about the size of Meteor Crater formed in rock is more nearly proportional to the kinetic energy of the projectile, as found by Gault (1973) for small experimental impact craters in rock, than it is to the momentum of the projectile, as predicted by Öpik (1958) and found by Schmidt (1980) for small impact craters in sand. If the rms impact velocity of 20 km s^{-1} obtained for Earth-crossing asteroids is adopted for the projectile that formed Meteor Crater, a spherical asteroid of meteoritic iron about 42 m in diameter has the kinetic energy required to form the initial 1.16 km diameter crater.

General scaling rules derived from dimensional analysis (Holsapple & Schmidt 1982) are a useful guide in extrapolating from the code calculations for Meteor Crater to obtain dimensions of craters produced by impact of Earth-crossing bodies ~0.5 to 10 km diameter, comparable to those discovered at the telescope. Terrestrial impact craters larger than about 3 to 4 km diameter differ in an important way from Meteor Crater, however, and account must be taken of this difference. In these larger craters, the rock walls of the initial craters have collapsed and slumped toward the centers of the craters. Similar collapse has occurred in nearly all craters on the Moon larger than 25 km diameter. From measurement of the cumulative widths of the terraces formed by the slumped blocks along the walls, the diameter of the 90 km diameter lunar crater Copernicus is estimated to have been increased more than 35% by wall collapse (Shoemaker 1962). A conservative value of 30% enlargement by collapse will be used here for estimation of the final crater diameter (cf Shoemaker et al 1979). To calculate the size of projectile required to form a 10 km diameter crater on Earth, for example, an initial crater only (1/1.3) × 10 km = 7.69 km diameter should be compared with Meteor Crater.

For two initial craters of similar form produced by projectiles with the same impact velocity (e.g. 20 km s^{-1}) in target rocks of the same strength, the ratio of the diameters of the projectiles that formed them is given by the following equation based on the Holsapple-Schmidt scaling rules (Wetherill & Shoemaker 1982):

$$d_2/d_1 = (\delta_1/\delta_2)^{(1+\beta-\gamma)/(3-\alpha)}(\rho_2/\rho_1)^{(1+\gamma)/(3-\alpha)}(D_2/D_1)^{3/(3-\alpha)}, \qquad (1)$$

where d_1 and d_2 are the diameters and δ_1 and δ_2 the densities of the two projectiles, ρ_1 and ρ_2 are the densities of the target rocks at the sites of the two craters, D_1 and D_2 are the corresponding crater diameters, and α, β, and γ are scaling constants. Setting $d_1 = 42$ m and $\delta_1 = 7.86$ g cm^{-3} for the Meteor Crater projectile, $\rho_1 = 2.3$ g cm^{-3} for the mean density of the rocks and $D_1 = 1.16$ km for the diameter of Meteor Crater, $\delta_2 = 2.38$ g cm^{-3} for the effective density of an impacting S-type asteroid (Shoemaker et al 1979), $\rho_2 = 2.6$ g cm^{-3} for average rocks on the continental shields, $D_2 = 7.69$ km as the diameter of the initial crater that collapses to 10 km diameter, $\alpha = 0.39$ as a representative value intermediate between theoretical limits found by Holsapple & Schmidt (1982), $\beta = 0.11$, which is consistent with the value preferred by Schmidt (1980), and $\gamma = 0.06$, which is consistent with impact experiments in basalt targets, a diameter $d_1 = 0.63$ km is found as a representative diameter for an asteroid that produces a 10-km crater by impact on a continent.

An entirely independent estimate of the projectile diameter and energy can be made by use of an empirical scaling relationship based on experimental explosion craters (Nordyke 1961, 1962, Shoemaker et al 1963, Nordyke 1977, Shoemaker 1977, Shoemaker et al 1979). As modified by Shoemaker & Wolfe (1982) to account for differences in density of the target rocks, the diameter, D_t, of a terrestrial impact crater can be estimated from

$$D_t = c_f K_n (W \rho_a/\rho_t)^{1/3.4}, \qquad (2)$$

where c_f is the crater collapse factor (nominally 1 for craters $\lesssim 3$ km diameter and 1.3 for craters $\gtrsim 4$ km in diameter), $K_n = 0.074$ km kilotons$^{-1/3.4}$ is an empirical constant derived from the diameter and explosive yield for the Jangle U nuclear crater, $\rho_a = 1.8$ g cm^{-3} is the estimated density of the alluvium at the Jangle U site in Yucca Flat, Nevada, ρ_t is the mean density of the target rocks, and $W = \pi d^3 \delta v^2/(12 \times 4.19 \times 10^{10})$ kilotons TNT equivalent is the kinetic energy of a projectile of diameter d, density δ, and velocity v, all measured in cgs units. Inversion of Equation (2) to obtain the kinetic energy of the Meteor Crater projectile gives an estimated energy of 15 megatons TNT equivalent, in agreement with the code calculation of Roddy et al (1980).

The success of Equation (2) rests on the choice of the 78 m diameter Jangle U crater for determination of the scaling coefficient K_n. Jangle U was selected because the initial energy density in the rocks shocked by nuclear explosion is comparable with that produced by asteroid impact (Shoemaker 1963), the explosion was at a scaled depth appropriate for comparison of explosion craters with most impact craters (cf Holsapple 1980), and the alluvium in Yucca Flat has a low strength, as required for scaling by Equation (2) from an experimental crater less than 100 m diameter with impact craters larger than 1 km that are formed in comparatively strong rock. The suitability of the strength properties of the Yucca Flat alluvium for scaling from small nuclear craters to large impact craters was judged on the basis of similarity of geometry of deformation of the material in the walls and floor of nuclear craters formed in the alluvium to that observed in larger impact craters (Shoemaker 1963). Applying Equation (2) to estimate the energy required to form a 10 km diameter impact crater, we get 1.04×10^4 megatons TNT; an asteroid with this kinetic energy and a density of 2.38 g cm^{-3} traveling at 20 km s^{-1} has a diameter of 0.57 km. When appropriate allowance is made for the uncertainties in all the scaling constants used, the $\sim 10\%$ difference between this diameter and the one obtained by means of scaling with Equation (1) should not be regarded as significant.

A source of some further unertainty about the diameters of craters produced by asteroid and comet impact arises from effects of variation of impact angle. Code calculations of oblique impacts of asteroids are sufficiently difficult that none have yet been published, although codes exist and have been used to study oblique impact of small projectiles at much lower speeds, primarily in metal targets. Gault (1973) found that the diameters of small experimental craters formed by relatively low-speed impact in strong rock were approximately proportional to $(\sin i)^{2/3}$, where i is the elevation angle of impact. This relationship suggests that craters produced by asteroid impact at a modal elevation angle near 45° might have diameters 30% smaller than craters produced at vertical incidence.

It is not at all clear, however, that the Gault relationship applies to hypervelocity impact craters with diameters near 10 km, because coupling of the projectile to the target and the relative dependence of crater dimensions on rock strength and gravity vary with projectile velocity and energy. The principal result of changing impact angle in large hypervelocity impacts probably is to change the effective scaled depth of penetration of the projectile about in proportion to sin i. The net effect of this change on the diameter of the crater may be similar to the effect due to change of scaled depth of burst of explosion craters (Nordyke 1961, 1962).

The scaled depth of burst of the Jangle U crater, 5.2 m kt$^{-1/3.4}$ (kt = kiloton), is apparently equivalent to the effective depth of penetration for average S-type asteroids impacting in average continental rocks at vertical incidence. The dependence of crater diameter on depth of burst found for explosion craters is nearly linear at this scaled depth (Nordyke 1962), and the maximum decrease in diameter of the crater as the scaled depth decreases to 0 is only about 9.5%. A functional dependence of crater diameter on impact angle might therefore be written as

$$D_i = [1 - 0.095(1 - \sin i)] D_{90}, \tag{3}$$

where D_i is the mean diameter of a crater formed at impact angle i and D_{90} is the diameter of the crater formed by impact at vertical incidence; at a modal angle of about 45°, the mean diameter of the crater would be only $\sim 3\%$ smaller than the diameter produced at vertical incidence. If the above analysis is approximately correct, neglect of the impact angle in the calculation of mean crater diameter generally introduces an error considerably smaller than the error due to uncertainty about the crater scaling constants. As i becomes very small, the most evident effect is that the crater produced will be noticeably elongate in the direction of the trajectory, as is probably illustrated by the lunar craters Messier and Messier A. However, the frequency distribution of incidence angle is such that very few cases of impact at i approaching 0° are expected (Shoemaker 1962).

Present Cratering Rate by Asteroid and Comet Impact

In order to obtain the total production of craters larger than some specified diameter, the frequency distribution of size or energy of the impacting bodies or, alternatively, the frequency distribution of the craters produced must be known. The size distribution of the discovered Earth-crossing asteroids listed in Table 1 is strongly biased by observational selection. Large, bright objects are more easily discovered than small, faint ones. Wetherill & Shoemaker (1982) estimate that discovery may be roughly 20% complete for objects $\geqslant 10$ km diameter, whereas it is only 1 to 2% complete for objects $\geqslant 1$ km diameter. The discovery of bright Earth-crossing comets may be somewhat more complete than is the case for the brightest Earth-crossing asteroids (Shoemaker & Wolfe 1982), but we are hampered by a lack of accurate information on the actual sizes of the comet nuclei. The distribution of nuclear magnitudes of short-period comets suggests that the distribution of cumulative frequency, N_d, has the form $N_d \propto d^{-\lambda}$, where d is the nucleus diameter and the size index, λ, is close to 2 (Shoemaker & Wolfe 1982). A nearly identical size index is indicated by the distribution of absolute magnitudes of faint main-belt asteroids (van Houten et al 1970). The size distribution of craters on the lunar maria, on the other hand, suggests that the size index of objects larger than ~100 m that have struck the Moon over the last 3.3 Gyr has been significantly less than 2.

The density of craters with diameters $\geqslant 10$ km on 3.3 Gyr old lunar mare surfaces is about half that predicted from a steady flux of Earth-crossing bodies equal to the present flux (Shoemaker et al 1979); the apparent discrepancy is no greater than the possible error of estimation of the present cratering rate. It is reasonable to suppose, therefore, that the larger solid objects that impacted the Moon in the last 3.3 Gyr are related in origin to the present Earth-crossing bodies, and that the size and energy distributions of these objects were similar to the size and energy distributions of the present population of Earth crossers.

The size distribution of craters on the lunar maria between 3 and 100 km diameter is well represented by a power function with a size index of 1.7 (Shoemaker et al 1963). Craters at the small end of this size range have not collapsed, whereas all the largest craters have been enlarged by collapse. Correcting for collapse, in order to obtain the diameter distribution of the initial craters, yields a size index for initial crater diameters of 1.84. As $D_t \propto W^{1/3.4}$ (Equation 2) and $d \propto W^{1/3}$, the size index for impacting bodies of the same density and specific kinetic energy is given by $\lambda = 1.84 \times 3/3.4 = 1.62$. This low value of λ indicates that the ratio of large bodies to small bodies that struck the Moon in the last 3.3 Gyr is much higher than expected from the magnitude distributions of comet nuclei or small main-belt asteroids (cf Shoemaker et al 1963). The high proportion of large objects may be due to relatively frequent evolution of large short-period comets of the Encke-type into Earth-crossing asteroids, whereas the mass of most small short-period comets may usually be dissipated, and relatively few become asteroidal objects with long dynamical lifetimes.

Of the 3.2 Earth-crossing asteroids equal to or brighter than absolute magnitude 18 estimated to strike the Earth each million years, suppose that half are C-type and half S-type. The mean diameter of a magnitude 18 asteroid is estimated to be 0.89 km for S types and 1.73 km for C types (Shoemaker et al 1979). If the size index for both types is 1.62 and we use 0.57 km as the mean diameter required for an impacting S-type body to produce a 10-km crater, then, on average, $1.6 \times (0.89/0.57)^{1.62} = 3.3$ S-type asteroids that are capable of producing craters $\geqslant 10$ km diameter strike the Earth per million years. From Equation (2), using an estimated effective density of 1.7 g cm^{-3} (Shoemaker et al 1979), the diameter of an average C-type asteroid that will produce a 10-km crater is 0.61 km. Thus, on average, $1.6 \times (1.73/0.61)^{1.62} = 8.7$ C-type asteroids that are capable of producing craters $\geqslant 10$ km diameter strike the Earth each million years. An average of about 1/3 of the 12 total S- and C-type asteroids actually hit the continents each million years, on average, where they produce about 4 craters 10 km diameter or larger.

The derived cratering rate is sensitive to the fraction of C-type asteroids, but the minimum and maximum possible cratering rates, corresponding respectively to no C-type asteroids and all C types, do not deviate by more than $\pm 45\%$ from the rate derived for the case of one-half C types. Accounting for comet impact, the total cratering rate should be increased by ~10% to ~30% over that obtained from asteroid impact alone. Assuming that the errors are distributed lognormally, the log probable error (log PE) of the estimated crater production rate may be roughly evaluated as follows: log PE of the estimated Earth-crossing asteroid population $\simeq 0.18$; log PE due to uncertainty about crater diameters obtained from the scaling formula used $\simeq 0.18$; log PE due to uncertainty about the fraction of C-type asteroids $\simeq 0.18$. From the rms of the logs, the final cratering rate has a probable error of the order of a factor of 2. A systematic error may reside in the mean bulk densities assigned to C- and S-type asteroids. In the calculation of asteroid bulk densities by Shoemaker et al (1979), allowance was made for 24% porosity produced by impact brecciation. If all the asteroids were compact rather than fragmental, the final calculated cratering rate would be increased by 14%.

Few telescopic observations have been made of Earth-crossing bodies smaller than about 0.5 km diameter, but an estimate of the energy-frequency distribution of these smaller bodies can be made with the aid of the size-frequency distribution of the lunar craters. The estimated rate of collision with the Earth of bodies in the energy range of 1 kiloton to 10^5 megatons TNT equivalent is illustrated in Figure 1. The frequency of collision at 1.04×10^4 megatons TNT equivalent energy corresponds to the production rate of 10-km craters estimated above. In the energy range from 1 kiloton to 10,000 megatons, the extrapolated frequencies are from a smoothed crater-size distribution based on the observed crater-size distribution in Mare Cognitum, determined from Ranger VII television images of the Moon (Trask 1966). The preferred crater diameter scaling relationship is taken to be $D \propto W^{1/3.4}$, but extrapolated frequencies based on $D \propto W^{1/3.3}$ and $D \propto W^{1/3.5}$ are also shown for comparison. A corrected

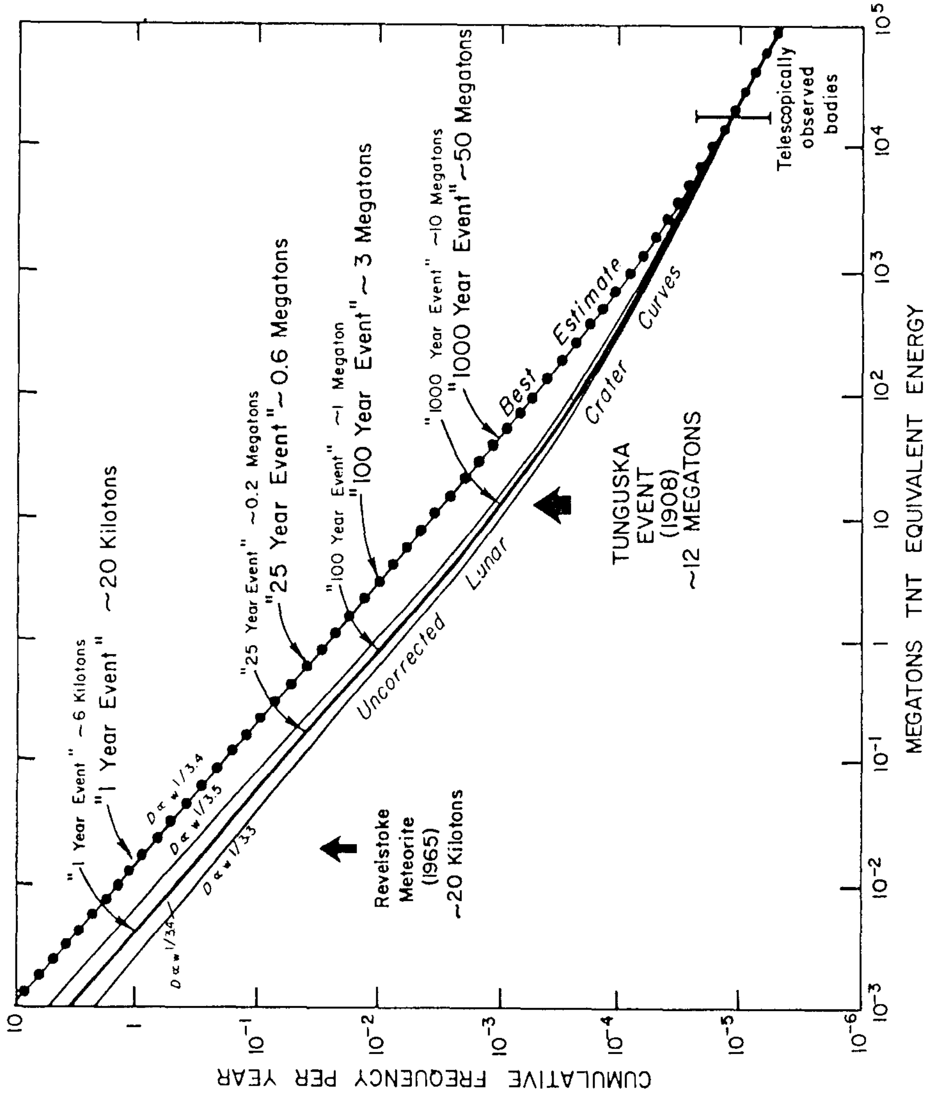

Figure 1 Estimated cumulative frequency distribution of kinetic energy of bodies colliding with the Earth.

frequency distribution, labeled *Best Estimate*, is based on the assumption that two thirds of the 10 km diameter craters counted by Trask (1966) predate the mare lavas that form the surface of Mare Cognitum, as suggested by studies of craters on the lunar maria by Neukum et al (1975).

Historic Collisions

The most energetic, historically well-documented encounter with the Earth of an Earth-crossing body produced a great meteoric fireball over the Podkamennaya-Tunguska River region of Siberia on the morning of June 30, 1908 (Krinov 1966). Traveling from southeast to northwest, the meteor passed nearly over the town of Kirensk; the endpoint of the trajectory was about 60 km northwest of the remote trading post of Vanovara, over a very sparsely inhabited part of the Siberian tiaga. The meteor was observed from distances as great as 600–1000 km from the endpoint; the atmospheric shock was audible at still greater distances. Trees were knocked down at distances up to 40 km from the endpoint, and circumstantial evidence suggests that dry timber was ignited by thermal radiation from the fireball at distances up to 15 km from the endpoint. Intensive investigation by expeditions from the Soviet Academy of Sciences carried out over many decades has shown that the Tunguska bolide disintegrated in the atmosphere; it deposited most of its kinetic energy at an estimated altitude of ~8.5 km (Ben-Menahem 1975). Only microscopic spheres of glass and magnetite, formed by ablation, reached the ground (Florensky 1963).

Long-period atmospheric gravity and acoustic waves excited by the atmospheric shock were well recorded on weather-station barographs in Siberia and southern England; the passage of these waves in both the direct and reverse paths was recorded on a barograph at Potsdam, Germany. Coupling of the air wave to the ground near the endpoint produced seismic waves detected at Irkutsk, Tashkent, Tiflis, and Jena; local coupling of the air wave to the ground as it passed over some seismic stations was also detected. From the English barograms published by Whipple (1930) it is possible to estimate the kinetic energy of Tunguska bolide. Detailed analysis by Hunt et al (1960) indicates an energy of 12.5 megatons TNT equivalent. Scaling from large nuclear airbursts, Shoemaker (1977) independently found an energy of ~12 megatons TNT; amplitudes of the air waves recorded on barographs in Siberia are consistent with this energy. However, a more recent analysis of the propagation of the air wave by ReVelle (personal communication, 1981) yields an estimated energy of ~30 megatons.

On the basis of a thorough study of the seismic records, Ben-Menahem (1975) estimated the energy at 12.5 ± 2.5 megatons. The distance to which trees were felled near the endpoint is consistent with a ~13-megaton explosion at an altitude of ~ 8 km (Ben-Menahem 1975), and, scaling from the effects of nuclear weapons (Glasstone 1964), the ignition of wood by the thermal radiation also suggests an energy of the order of 10 megatons.

Turco et al (1982) have recently reinterpreted Ben-Menahem's work on the seismic records and suggested an energy of $\gtrsim 670$ megatons. As the bolide was certainly stopped in the atmosphere, the near and far record of the air waves and the extent of felling and ignition of trees show unequivocally that the estimate of Turco et al is $\gtrsim 20$ times too high.

From Figure 1, it may be seen that the "best estimate" of the frequency of a 12-megaton encounter with the Earth is about once every 300 $\overset{\times}{\div}$ 2 years; a 30-megaton encounter occurs about every 700 $\overset{\times}{\div}$ 2 years. There is a ~ 12 to $\sim 40\%$ chance that a 12-megaton encounter will occur in an interval of 75 years (the approximate time elapsed since 1908) and a ~ 5 to $\sim 20\%$ chance that a 30-megaton event will occur during this interval. On the basis of the predicted frequency, estimates of the energy of the Tunguska event in the range of 10–15 megatons appear somewhat more likely than ReVelle's estimate of 30 megatons. There is no more than a 1.5% chance of encounter of a 670-megaton bolide in an interval of 75 years.

The physical characteristics of the Tunguska object remain unsolved, as only ablation products have been recovered. At a typical encounter velocity of 20 km s^{-1}, a 12-megaton stony asteroid with a density of 2.4 g cm^{-3} has a diameter of 60 m. A stony body this small will not normally survive passage through the atmosphere. Almost any body of rock tens of meters across can be expected to be riven with structural flaws, especially fragments produced by collisions in the asteroid belt. Because of their low strength, nearly all stony bodies less than ~ 150 m diameter are sheared apart by aerodynamic stress in the lower atmosphere (cf Passey & Melosh 1980). Depending on the strength and structure of the object, a cascade of fragmentation may occur, and the body can be pulverized, ablated, and essentially stopped in the air. Thus, contrary to a common misconception, there is no mystery about the failure of the Tunguska bolide to reach the ground and produce a crater. The fact that it was stopped in the air does not provide any clues about the object other than that it was not a large iron meteorite or a pallasite (stony iron). Failure of numerous Soviet expeditions to find macroscopic meteorite fragments on the ground, on the other hand, does suggest that the bolide was composed of very weak or friable stony material or, perhaps, very small rocky particles embedded in ices.

Whipple (1930) suggested that the Tunguska object may have been a comet, and this concept appears to have gained general acceptance among informed Soviet investigators (Krinov 1966). Kresák (1978) has shown that the approximate trajectory of the meteor was consistent with the hypothesis that the Tunguska bolide was a fragment of Comet Encke. The strongest evidence that the Tunguska object was a comet comes from the distribution of very fine particles in the high atmosphere on the night following the encounter; an enormous, bright noctilucent cloud extended westward from Siberia to Ireland (~ 6000 km) and as far south as 45°N latitude (Krinov 1966, Fesenkov 1962, 1966). The distribution of the cloud corresponds approximately to the pattern expected for encounter of a possible cometary tail associated with the bolide. Turco et al (1982), on the other hand, have pointed out that normal upper-atmospheric circulation could have spread dust, ice particles, and NO_x over much of the region where bright skies were observed on the night of June 30, 1908. Some of the observed optical effects may have been due to airglow from chemical reactions of NO_x produced in the atmosphere by the Tunguska fireball.

In February, 1947, another brilliant meteoric fireball was observed over Siberia, this time in the eastern coastal region of Sikhote-Aline (Krinov 1966). The fireball was due to atmospheric entry of an iron meteorite that broke up at an altitude of about 6 km and yielded more than 380 fragments that struck the ground. A strewn field of more than 100 craters larger than 0.5 m diameter was formed; the largest crater was 26.5 m in diameter. In four expeditions of the Soviet Academy of Sciences, more than 23 tons of meteorite fragments were collected; a total mass of 70 tons is estimated to have fallen. On the basis of an orbit computed by Fesenkov (1951), the encounter velocity was ~ 14 km s^{-1} and the kinetic energy of the bolide was ~ 1.7 kilotons TNT equivalent. From Figure 1, about 7 $\overset{\times}{\div}$ 2 objects with this energy encounter the Earth each year, of which ~ 2 $\overset{\times}{\div}$ 2 enter the atmosphere over the continents. However, only $\sim 6\%$ of the meteorites recovered from observed falls are irons (Mason 1962), and only one quarter to one half of the bolides producing very bright fireballs apparently are strong enough to yield recoverable meteorites (Ceplecha & McCrosky 1976, Wetherill & ReVelle 1981). The predicted fall rate on the continents of iron meteorites with the energy of the Sikhote-Aline bolide, therefore, is once per 10 to 80 years, consistent with the record of one such fall in the time since civilization over most of the world has become scientifically observant. Perhaps one or more such falls occurred in this century that were not recorded.

On March 31, 1965, a brilliant fireball seen from distances as far away as 750–800 km flashed over the sky of southern British Columbia. Tiny fragments, aggregating about 1 g, of carbonaceous meteorite were later found on the snow near Revelstoke (Folinsbee et al 1967), and a rich collection of magnetite and silicate glass spherules was obtained from airborne collectors after the air mass penetrated by the meteor had passed over the United States (Carr 1970). A sensitive microbarograph array in operation at that time by the National Bureau of Standards at Boulder, Colorado, recorded relatively long-period acoustic waves excited by the passage of the Revelstoke bolide (Shoemaker & Lowery 1967). Analysis of the air-wave record shows that the energy of the initial Revelstoke object was ~20 kilotons TNT equivalent. At an assumed modal velocity of 20 km s^{-1}, the indicated initial mass of the body was ~500 tons. An object with this or greater energy encounters the Earth about once a year (Figure 1), and one will penetrate the atmosphere over North America about once every 25 ± 2 years. The Revelstoke fireball was the most energetic meteor detected over North America by the Boulder microbarograph array, which was operated for less than 20 years. The largest event of probable meteoric origin observed anywhere over the globe in this time period had an energy of 0.5 megatons and was located in the South Atlantic; the occurrence of this event in a ~20-year time interval is also consistent with the frequency predicted from the Best Estimate curve of Figure 1.

Small Impact Craters Formed by Iron Meteorites

Although the atmosphere stops most stony bodies less than ~150 m diameter (energy less than ~200 megatons), smaller bodies of strong, high-density iron can reach the ground and form craters. If the frequency with which crater-forming iron meteorites fall on the continents is about one to several times per century, as suggested above, numerous small young impact craters must have been produced. Most of these would not be large enough to survive in easily recognizable form for more than a few centuries, but craters in semiarid to arid regions and most craters larger than several hundred meters diameter can survive for thousands or tens of thousands of years.

Prehistoric impact craters with associated iron or stony-iron meteorites are known from 13 localities around the world (Table 2). As expected, most have been found in semiarid and arid regions. The largest is the 1.2 km diameter Meteor Crater of Arizona, which was formed in the late Pleistocene between ~20,000 and ~30,000 years ago (Shoemaker 1963, Shoemaker & Kieffer 1974). Assuming that the fraction of iron objects of any given energy is 0.015 to 0.03, as estimated above, the frequency of encounter with the Earth of an iron asteroid with an energy of ~15 megatons can be estimated from Figure 1 at about once per 6300 to 50,000 years. On this basis, a feature like Meteor Crater would be formed on the continents once every ~20,000 to ~150,000 years. The lower bound of the predicted recurrence interval is comparable with the age of Meteor Crater.

Physical studies of asteroids indicate that the proportion among telescopically observable objects that are neither C- nor S-type is 10% (Zellner 1979), of which half or more may be iron objects. Using a fraction of 0.05 irons, a production rate on the continents of one impact crater the size

Table 2 Prehistoric impact craters with associated meteorites

Locality	Number of craters	Diameter of largest crater (m)	Age	References
Haviland, Kansas, USA	1	14	Holocene ?	Nininger & Figgins 1933
Dalgaranga, W.A., Australia	1	26	Holocene ?	Nininger & Huss 1960
Sobolev, Siberia, USSR	1	51	Holocene ?	Khryanina & Ivanov 1977
Morasko, Poland	8	60	Holocene ?	Pokrzywnicki 1964
Campo del Cielo, Argentina	20	90	Holocene ?	Cassidy et al 1965
Wabar, Saudi Arabia	2	91	6400 ± 2500 yr	Philby 1933, Storzer & Wagner 1977
Kaalijarv, Estonia	7	100	Holocene	Krinov 1961
Henbury, N. T., Australia	14	150	4200 ± 1900 yr	Milton 1968, Storzer & Wagner 1977
Odessa, Texas, USA	5	168	~25,000 yr	Evans 1961
Boxhole, N.T., Australia	1	175	Holocene ?	Madigan 1937
Monturaqui, Chile[a]	1	455	Late Pleistocene ?	Sanchez & Cassidy 1966
Wolf Creek, W. A., Australia	1	875	Pleistocene	Fudali 1979
Meteor Crater, Arizona, USA	1	1200	25,000 ± 5000 yr	Shoemaker & Kieffer 1974

[a] All meteoritic material discovered at Monturaqui, Chile, is completely oxidized, but the nature of the oxide shows that the meteorite was an iron. Many specimens of unoxidized iron meteorites reported from other localities in Chile may have been transported from this site by the prehistoric Indians (Sanchez & Cassidy 1966).

Table 3 Small impact craters unaccompanied by discovered meteorites

Crater	Diameter (km)	Impact metamorphosed rocks	References
Aouelloul, Mauritania[a]	0.4	Yes	Chao et al 1966 Fudali & Cassidy 1972
Temimichat, Mauritania[a]	0.7	No	Fudali & Cassidy 1972
Pretoria Salt Pan, South Africa	1.0	No	Wagner 1922 Milton & Naeser 1971
Lonar Lake, India	1.7	Yes	Fudali et al 1980
Tenoumer, Mauritania[a]	1.8	Yes	French et al 1970 Fudali & Cassidy 1972 Fudali 1974
Roter Kamm, southwest Africa	2.4	Yes?	Fudali 1973

[a] The three craters in Mauritania may have been formed simultaneously $(3.1 \pm 0.3) \times 10^6$ years ago by fragments produced from aerodynamic breakup of a single initial projectile (Dietz et al 1969, Fudali 1976).

of Meteor Crater every 23,000 $\stackrel{\times}{\div}$ 2 years is obtained, which is indistinguishable from the age of Meteor Crater. On the same basis, about 2 $\stackrel{\times}{\div}$ 2 craters ≥ 750 m diameter should have been formed on the continents in the last 23,000 years; two have been discovered (Table 2), but the smallest (Wolf Creek) may be older than 23,000 years. A total of 8 craters ≥ 100 m diameter with associated iron meteorites have been found (Table 2), but roughly 1000 should have been formed in the last 20,000 years. Completeness of discovery clearly drops very rapidly for impact craters below ~0.5 km diameter.

In addition to the craters with associated iron meteorites, 6 other well-defined young craters of impact or probable impact origin are known that are smaller than 3 km diameter (Table 3). Again, most of these have been discovered in arid regions. No meteorites have been found at these craters, but projectiles of unusually high strength or density probably are required to form craters of this size; iron or stony-iron bodies are the most likely candidates. About 50 $\stackrel{\times}{\div}$ 2 craters ≥ 1 km diameter probably were formed on the continents by impact of iron meteorites in the last million years. Hence, ~ 10 times as many craters as are shown in Table 3 may remain to be discovered.

Young Large Impact Craters

As 4 $\stackrel{\times}{\div}$ 2 craters ≥ 10 km diameter are predicted to be formed on the continents per 10^6 years, there is an 85% chance that at least one in this size range was actually produced in the last million years. Craters 10 km in diameter are large enough to survive in recognizable form in most parts of the world for times of the order of a million years. However, we may reasonably expect that any meteorite fragments that may have been associated with them have long since disappeared by weathering and erosion. Identification of impact origin, therefore, must rest on the structure of the craters (Shoemaker & Eggleton 1961, Dence et al 1977) and on the various products of shock metamorphism (French & Short 1968).

The best known young large impact crater contains Lake Bosumtwi, the sacred lake of the Ashanti tribe of Ghana. It is 10 km in diameter, and the fission-track age of the Bosumtwi impact glass is 1.04 ± 0.11 Myr (Storzer & Wagner 1977). The crater is the source of the contemporaneous Ivory Coast strewn field of tektites (Schnetzler et al 1967, Kolbe et al 1967). The impact origin of the Bosumtwi crater was suspected by Maclaren (1931) and confirmed by the discovery of coesite in the strongly shocked ejecta (Littler et al 1962).

A ~7 km diameter crater, referred to as Zhamanshin and located north of the Aral Sea in Kazakhstan, was recently recognized as an impact crater by Florensky (1975, 1977). A fission-track age of 1.07 ± 0.05 Myr was obtained from impact glass at Zhamanshin (Storzer & Wagner 1977). The crater appears to be the source of the nearby irghizite (wet tektite) strewn field (Florensky 1975, King & Arndt 1977).

Another large young impact crater in the Soviet Union, containing Lake Elgygytgyn (located near the Arctic coast of eastern Siberia), is 18 km diameter. The impact origin of this remote crater now appears to be well documented (Gurov et al 1978, 1979); a K/Ar age of 3.5 ± 0.5 Myr was reported for impact glass from the site. Assuming that the size index of large terrestrial craters is 1.84, the production rate of craters ≥ 18 km on the continents is $(1.4 \stackrel{\times}{\div} 2) \times 10^{-6}\ \mathrm{yr}^{-1}$, and there is a 99% probability that at least one 18-km crater will be formed in a time interval of 3.5 Myr. The Elgygytgyn crater fulfills this prediction, but it is also likely that one or two other craters or eroded impact structures of this size and approximate age also exist.

Large, million-year-old craters can be deeply eroded or filled by sediments in humid regions or completely obliterated in areas of glaciation and on the continental shelves. Moreover, the geology of much of the land surface of the Earth remains to be mapped in detail. Hence, we should not expect that all the young continental impact structures ≥ 10 km diameter have been recognized. A case in point is the source of the 700,000-year-old Australasian tektites. Their origin as terrestrial impactites derived from continental rocks is well established on chemical, isotopic, and mineralogical grounds (Chao et al 1962, Walter 1965, Taylor 1973, King 1977). Dietz (1977) postulated that the Australasian tektites were derived from

Elgygytgyn, and Taylor & McLennan (1979) argued for Zhamanshin as the source. Both craters appear to be eliminated as candidates on the basis of their ages. Judging from the modest strewn field of tektites associated with the 10-km Bosumtwi crater, Zhamanshin is also too small to be a likely source for the voluminous Australasian tektites. Apparently at least one large (>10 km diameter?) 700,000-year-old impact structure remains to be found somewhere on the continents, probably on the Asian land mass (cf Taylor & McLennan 1979).

Ancient Phanerozoic Impact Structures

When the impact record on the continents is examined for features older than a few million years, most of the craters are found to have been lost by erosion or by burial beneath sediments. The oldest known impact craters that preserve remnants of their original topography are the 14.7 Myr old Ries crater (27 km diameter) and nearby Steinheim Basin (3.4 km) in the Schwabian Alb of southern Germany (Pohl et al 1977, Reiff 1977). Some ancient craters, such as the Holleford crater (Cambrian) and the Brent crater (Ordovician), both in Ontario, and the Flynn Creek crater (Devonian) in Tennessee, were formed on the floors of shallow epicontinental seas and were buried beneath marine sediments (Dence & Guy-Bray 1972, Roddy 1977). Most older impact sites, however, can only be recognized by the structural disturbance of the bedrock and, where preserved, associated shock-metamorphosed rocks. In crystalline bedrock, the most easily recognized structural feature is a lens of breccia that was formed beneath the original crater floor. In stratified sedimentary targets, a highly deformed central structural uplift surrounded by a circular structural moat of down-dropped rock is commonly present. This distinctive structural pattern is the product of collapse of the initial crater. Very large structures (>50 km) can be considerably more complex (Dence et al 1977).

The record of impact structures older than a few million years essentially begins at craters or structures with diameters greater than 2 to 3 km. Fewer than 10 ancient features whose impact origin is firmly determined are smaller than 3 km, but many are close to this size. This limit corresponds approximately to the size of craters formed by the smallest stony asteroids (~ 100 to ~ 150 m diameter) expected to survive passage through the atmosphere. The frequency of crater production probably jumps by a factor of ~ 10 across the ~ 3-km threshold.

About 70 craters and structures of probable impact origin that are larger than 3 km diameter have been identified throughout the world (Dence 1972, Robertson & Grieve 1975, Masaitis 1975, Grieve & Robertson 1979). Over 90% have been found in the United States, Canada, the Soviet Union, western Europe, and Australia, which constitute the major portion of the world most thoroughly investigated by geologists. It is also the part most thoroughly surveyed for impact craters. By far the largest number of impact structures occurs on the geologically stable platform or shield areas of the continents, called cratons, where ancient impact features tend to be preserved longest and where they are usually most easily recognized. Only the impact record from the cratons is sufficiently complete for meaningful comparison with the present cratering rate predicted from astronomical observations. Even on the cratons, however, most impact structures less than 10 km diameter evidently have been lost by erosion or have been so deeply eroded as to preclude recognition. The mean lifetime of 10-km impact structures against erosion has been estimated by Grieve & Robertson as 300 Myr.

Converting the estimated present cratering rate by asteroid impact given for the whole Earth, the rate per unit area is $(2.4 \stackrel{\times}{\div} 2) \times 10^{-14}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ craters $\geqslant 10$ km diameter. Adding cratering by comet impact increases this rate by ~ 10–30%. Grieve & Dence (1979) found that the production over Phanerozoic time (the last ~ 600 Myr) of craters $\geqslant 20$ km diameter was $(0.36 \pm 0.1) \times 10^{-14}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ on the North American craton and $(0.33 \pm 0.2) \times 10^{-14}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ on the European craton. Averaging these rates and assuming a size index of 1.84 for the craters produced, the corresponding rate for craters $\geqslant 10$ km is $(1.24 \pm 0.36) \times 10^{-14}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$. This rate lies just within the estimated error bar of the estimated present rate for asteroid impact, but it is of interest to inquire whether the result of Grieve & Dence might be biased by erosional loss of some craters $\geqslant 20$ km diameter, particularly in the hearts of the Precambrian shields.

The most complete record of impact structures probably is preserved where the Precambrian rocks of the cratons are thinly veneered with Phanerozoic platform sediments (Grieve & Robertson 1979). Such an area is found in the Mississippi lowland of the United States. There, from a much smaller set of known structures, Shoemaker (1977) found a 10-km cratering rate of $(2.2 \pm 1.1) \times 10^{-14}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$, which is in excellent agreement with the estimated present rate. Within the errors of estimation, it appears that the cratering rate on the continents, averaged over intervals of the order of 10^8 years, has been relatively steady over Phanerozoic time.

Large Precambrian Impact Structures

Extrapolating to larger crater sizes with the size index of 1.84, the estimated present cratering rate on the continents is $6 \stackrel{\times}{\div} 2$ per 100 million years for 100 km diameter craters and $3 \stackrel{\times}{\div} 2$ per 100 million years for 140-km craters. Judging from the postmare lunar craters, the size distribution of craters $\geqslant 3$ km diameter probably follows a simple power law up to about 100 km, but it appears to steepen at sizes above 100 km. As the area of the continents has not increased more than about 25% during the last 500 million years and as the cratering rate appears to have been nearly steady, about 25 ± 2 craters ≥ 100 km diameter should have been formed on the continents in this time.

Only one 100 km diameter impact structure of Phanerozoic age (Popigai in the USSR) and two structures approaching 100 km (Puchezh-Katunk in the USSR and Manicouagan in Quebec) have so far been recognized (Grieve & Robertson 1979). One reason so few have been found may be that the entire crust responds isostatically when craters of this size are formed, and the initial relief is largely lost through quasi-viscous flow of the mantle and lower crustal rocks. Other geologic processes, such as volcanism, may be triggered by these large impacts, and entire impact structures may be covered by lava or the evidence bearing on their origin may be obscured by these secondary geologic effects.

As many as 5 to 10 impact structures ≥ 140 km diameter probably were formed on the continents during the Phanerozoic; none have yet been found. Over the preceding 2.5 billion years, 5 to 10 additional impact structures this size probably were formed. Two 140 km diameter Precambrian structures of probable impact origin have been recognized: the Sudbury Basin of Ontario and the Vredefort Dome in South Africa (Grieve & Robertson 1979). The impact origin of the 1840 ± 150 Gyr Sudbury Basin is well established from the shock metamorphism of rock fragments in a thick sequence of strongly shocked fallback material that is preserved in the center of the basin (French 1967, 1968). This material rests on a thick eruptive body of norite. Part of the eruptive material may be deep-seated magma whose formation was triggered by the impact, but considerable impact melt derived from the continental crust evidently is mixed with the norite (Hamilton 1970).

Although challenged by Nicolaysen et al (1963), the impact origin of the 1970 ± 100 Gyr Vredefort Dome is strongly indicated by its structure (Wilshire & Howard 1968), by the occurrence and orientation of shatter cones (Manton 1965), and by abundant veins of microbreccia called pseudotachylyte (Shand 1916) that locally contain coesite and stishovite, the high-pressure polymorphs of SiO_2 (Martini 1978), and various shock-metamorphic features such as planar dislocations and lamellae in quartz (Carter 1965, Lilly 1981) and the crystallographic configuration of feldspars in a granite at the center of the dome (Aitken & Gold 1968). Dietz (1963) suggested that the great Bushveld complex of strataform igneous rock, which lies north of the Vredefort Dome, might have been formed by an eruption of a sheet of basalt in response to another large Precambrian impact event. On the basis of a structural interpretation of the Bushveld, Hamilton (1970) elaborated on Dietz's suggestion and proposed that the Bushveld eruptive sheet occupies the ring moats of three overlapping impact structures, each of which is roughly comparable to or larger than the Vredefort structure. Hamilton supposed that these structures, including the Vredefort, were all formed simultaneously.

To account for such a multiple impact event, he suggested that the impacting bodies may have been fragments of a comet that was broken up in the atmosphere or by gravitational disruption. As shown by Emiliani et al (1981), neither a comet nucleus nor an asteroid of the required size could be broken up and separated any significant distance by aerodynamic forces. If the initial body were sufficiently elongate or even multiple to begin with, on the other hand, it could be readily broken by tidal forces and the parts separated sufficiently to produce separate impact structures. At least two fairly rapidly rotating Earth-approaching asteroids, 433 Eros and 1620 Geographos, are sufficiently elongate that they are scarcely bound by their own gravity and would be readily broken and separated by tidal forces on near-encounter with the Earth. They may be multiple bodies to start with. Hence, a comet is not necessarily the most likely parent of multiple projectiles that may strike the Earth almost simultaneously. It is entirely plausible, and even moderately probable, that a multiple impact event comparable to that postulated by Hamilton for the Bushveld has occurred in the last two billion years. In fact, a pair of impact craters at Clearwater Lakes, Quebec, is an example of a multiple impact on a somewhat smaller scale that occurred about 290 million years ago (Grieve & Robertson 1979).

Whether the Bushveld structural system was actually formed in the manner suggested by Hamilton is a separate question, however. As all three impact structures posited by him are as large or larger than the Vredefort, the rocks comprising the central uplifts of these structures should have been brought up from depths comparable to the depth of origin of the granite in the central dome of Vredefort. Much of the largest central uplift in the Bushveld area (Marble Hall uplift) appears to be composed of upper-crustal sedimentary and volcanic rocks. If this is correct, the presence of these rocks may pose a serious difficulty for Hamilton's model. Clearly, much further work is needed to test his intriguing hypothesis.

EFFECTS OF BOMBARDMENT ON TERRESTRIAL LIFE

Asteroids and comet nuclei larger than 1 km diameter will unequivocally extinguish life locally wherever they strike the Earth, but the area affected by each impact crater and its surrounding ejecta blanket is too small to be of much consequence to biological evolution, even for impacting bodies up to tens of kilometers diameter. As the size of the crater increases, however, a threshold is reached where the material ejected into the high atmosphere has a strong transient effect on global climate. Discovery by Alvarez et al (1980) of anomalous abundances of iridium and other elements in a claystone layer at the Cretaceous-Tertiary boundary suggests that impact of a fairly large asteroid or comet is associated in time with a major extinction of living species. This anomalous claystone layer, which has been recognized from about 40 localities around the world (Alvarez et al 1982, Pillmore et al 1982), appears to record the fallout of highly shocked material that was heavily contaminated by the constituents of the impacting body. Typical thicknesses of the claystone are 1–2 cm. Alvarez et al (1980) estimated that an impacting asteroid on the order of 10 km diameter and with an iridium abundance comparable to that of common stony meteorites would be required to supply the amount of iridium distributed globally in the claystone.

Suspension in the stratosphere of a few tenths of a gram of micron- to submicron-size dust per square centimeter would almost totally block sunlight from the Earth's surface (Gerstl & Zardecki 1982). Toon et al (1982) have estimated that the settling time of most of the stratospheric dust would be of the order of several months to half a year. Under these conditions, only the warming of the air by the heat stored in the oceanic thermosphere would prevent the troposphere from becoming nearly isothermal. In a short time, the mean surface temperatures over land areas would drop by several tens of degrees C.

A somewhat longer-lived transient climatic effect may be produced by large impacts in the deep ocean. Enough water can be injected into the high atmosphere to replace most of the stratospheric air with water vapor. Emiliani et al (1981) have suggested that after the dust and excess water have precipitated and the atmosphere clears, the remaining water vapor would lead to a greenhouse effect that would raise surface temperatures by more than 10°C above the preexisting ambient conditions. This type of transient effect probably persists for times of the order of years, as the equilibrium composition of the stratosphere would be reestablished only by the slow processes of photochemical dissociation of the H_2O and diffusion across the tropopause.

Still other biologically deleterious effects of large impacts may be associated with large quantities of NO_x produced in the high-temperature atmospheric shock wave (Park 1978, Park & Menees 1978) and possibly with contamination of the atmosphere by the constituents of the projectile itself (cf Hsü 1980).

The threshold size of impacting bodies at which biologically significant perturbations of the atmosphere and oceanic thermosphere are produced is very poorly understood. If the abrupt extinction of marine plankton and other species at the end of the Cretaceous is related to impact of a body large enough to produce the observed noble-metal anomaly in the boundary claystone, then projectile diameters on the order of 10 km are evidently above the threshold. On the basis of the estimated Phanerozoic cratering rate and the size distribution of postmare craters on the Moon, 10 km diameter projectiles struck the Earth with a mean frequency of once every $\sim 0.5 \times 10^8$ years during the Phanerozoic. From the long-term lunar impact record, the mean frequency of Earth impact of 10-km bodies back to 3.3 Gyr was about once per 10^8 years.

The threshold size of projectiles that might cause mass extinction of species in certain environments may be considerably smaller than 10 km diameter. At 5 km diameter, the frequency of impact is about four times as great as at 10 km. It is entirely possible that dozens of impact-related ecological jolts severe enough to be reflected in the paleontologic record were delivered to the biosphere during the Phanerozoic. The test of this possibility will require close scrutiny of the stratigraphic and paleontologic evidence.

Bodies larger than 10 km diameter can also hit the Earth. For example, the Earth-approaching asteroid 433 Eros has a 20% chance of colliding in the next 400 million years (Wetherill & Shoemaker 1982); the mean diameter of Eros is ~ 20 km. Over the span of Precambrian time back to 3.3 Gyr it is likely that several asteroids and comet nuclei in the 20–30 km diameter range struck the Earth. Whether the climatic perturbations produced by these giant impacts were much greater than those produced by 10-km bodies is not clear. It may be that the climatic perturbations were limited by saturation and that any material introduced into the atmosphere exceeding a certain limit simply fell out again rather quickly. On the other hand, prompt effects, such as heating of the atmosphere due to compression under the initial load of material, probably had no upper bound.

The lunar-crater record shows that the cratering rate at 3.9 Gyr was about 25 times higher than at present, and that between 3.9 and 3.3 Gyr it decayed approximately exponentially with a half-life near 10^8 years. A dozen or more objects larger than 20 km diameter may have struck the Earth in the few hundred million years after deposition of the earliest-recorded Precambrian sediments of the Isua complex, Greenland, at 3.8 Gyr. At still earlier times, the bombardment was even more intense. Whatever primitive organisms may have existed then probably were subjected to frequently repeated environmental insults on a global scale.

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