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Landscapes with Craters: Meteorite Impacts, Earth, and the Solar System

1.1. THE NEW GEOLOGY: METEORITE IMPACTS ON THE EARTH

During the last 30 years, there has been an immense and unexpected revolution in our picture of Earth and its place in the solar system. What was once a minor astronomical process has become an important part of the geological mainstream. Impacts of extraterrestrial objects on the Earth, once regarded as an exotic but geologically insignificant process, have now been recognized as a major factor in the geological and biological history of the Earth. Scientists and the public have both come to realize that terrestrial impact structures are more abundant, larger, older, more geologically complex, more economically important, and even more biologically significant than anyone would have predicted a few decades ago. Impact events have generated large crustal disturbances, produced huge volumes of igneous rocks, formed major ore deposits, and participated in at least one major biological extinction.

Before the 1960s, collisions of extraterrestrial objects with the Earth were not considered significant. Geologists did agree (and had agreed since the early 1800s) that pieces of extraterrestrial material did occasionally penetrate the atmosphere and strike Earth's surface, but the only visible results of such collisions were a collection of meteorites to study and display in museums, together with a few small and geologically short-lived meteorite craters, usually located in out-of-the-way desert areas (Fig. 1.1). Almost no one believed that extraterrestrial objects could produce major geological effects or that such projectiles could be any more than a local hazard.

This simple view has changed drastically, and the change reflects two major factors: (1) explorations of the solar system by humans and robotic spacecraft, which have established the importance of impact cratering in shaping all the planets, including Earth (*Taylor,* 1982, Chapter 3; 1992, Chapter 4); and (2) the ability to definitely identify terrestrial impact structures, especially large or ancient ones, by the presence of unique petrological and geochemical criteria, particularly the distinctive **shock-metamorphic effects** produced in rocks and minerals by the intense **shock waves** generated in impact events (*French,* 1968a; *French and Short,* 1968).

In the last few decades, geologists have gradually realized that collisions of extraterrestrial objects with Earth — and especially the rare but catastrophic impacts of kilometer-sized asteroids and comets — have significantly shaped Earth's surface, disturbed its crust, and altered its geological history (*French,* 1968a, 1990b; *Shoemaker,* 1977; *Grieve,* 1987, 1990, 1991; *Nicolaysen and Reimold,* 1990; *Pesonen and Henkel,* 1992; *Dressler et al.,* 1994).

The record of impacts on Earth is still being deciphered. Approximately 150 individual geological structures have already been identified as the preserved results of such impacts (*Grieve,* 1991, 1994; *Grieve et al.,* 1995; *Grieve and Pesonen,* 1992, 1996), and it is estimated that several hundred more impact structures remain to be identified (*Trefil and Raup,* 1990; *Grieve,* 1991). The known impact structures (Fig. 1.2) range from small circular bowls only a few kilometers or less in diameter (Fig. 1.1) to large complex structures more than 200 km in diameter and as old as 2 Ga (Figs. 1.3 and 1.4). Formation of the larger features, such as the Sudbury (Canada) and Vredefort (South Africa) structures, involved widespread disturbances in Earth's crust and major perturbations in the geologic history of the regions where they were formed.

In addition to the geological disturbances involved, impact events have produced several geological structures with actual economic value; a production value of about $5 billion per year has been estimated for North American

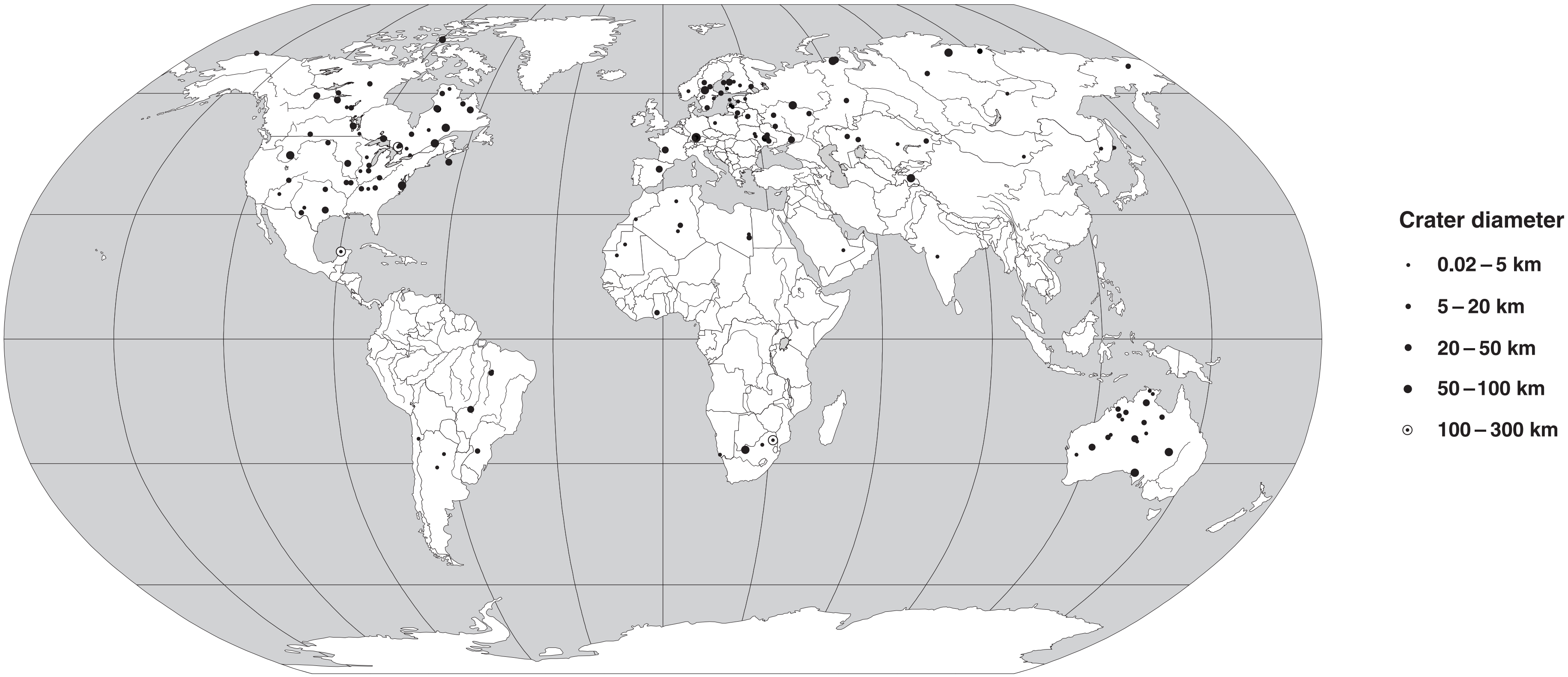
Fig. 1.1. A simple impact crater. Barringer Meteor Crater (Arizona), a young, well-preserved, and well-known impact crater, 1.2 km in diameter, has become the type example for small, bowl-shaped impact craters of the simple type. The crater was formed about 50,000 years ago when an iron meteorite approximately 30 m across struck the horizontal sediments of northern Arizona's Colorado Plateau. After decades of controversy, the impact origin of the crater has been firmly established by the presence of preserved iron meteorites, the recognition of unique shock-metamorphic features in its rocks, and geological studies that detailed the mechanisms of its formation. This aerial view, looking northwest, shows typical features of young simple impact craters: a well-preserved near-circular outline, an uplifted rim, and hummocky deposits of ejecta just beyond the rim (e.g., white areas at lower left). The uplifted layers of originally horizontal sedimentary target rocks can be seen in the far rim of the crater at the right. (Photograph copyright D. J. Roddy; used with permission.)

impact structures alone (*Grieve and Masaitis,* 1994). The economic products of impact structures include such diverse items as local building stone, diamonds, and uranium. Hydrocarbons (petroleum and gas) are an especially important product from impact structures (*Donofrio,* 1997; *Johnson and Campbell,* 1997). Large impacts crush and shatter the target rocks extensively beneath and around the crater; in a few structures [e.g., Ames (Oklahoma); Red Wing Creek (North Dakota)], the resulting breccia zones have served as traps for oil and gas. Within and around other impact craters, the other kinds of breccias produced by the impact have provided building stone [Ries Crater (Germany); Rochechouart (France)] and industrial limestone [Kentland (Indiana)]. In some cases, the sediments that subsequently fill the crater depressions may contain deposits of such economic materials as oil shale [Boltysh (Ukraine)], diatomite [Ragozinka (Russia)], gypsum [Lake St. Martin (Canada)], and lead-zinc ores [Crooked Creek (Missouri)].

The biggest impact-related bonanza (current production about $2 billion per year) is the Sudbury structure (Canada), which contains one of the largest nickel-copper sulfide deposits on Earth (*Guy-Bray,* 1972; *E. G. Pye et al.,* 1984; *Dressler et al.,* 1994; *Lightfoot and Naldrett,* 1994). The deposit occurs at the base of a large igneous body (the Sudbury Igneous Complex), which is in turn emplaced in a large, complex, and highly deformed impact basin nearly 2 b.y. old.

Terrestrial life itself has not escaped this cosmic bombardment. During the last 20 years an impressive amount of evidence has accumulated to show that at least one large impact event about 65 m.y. ago redirected biological evolution on Earth by producing the major extinction that now marks the boundary between the Cretaceous and Tertiary periods, the point at which the dinosaurs died and mammals (our ancestors) became major players in the history of terrestrial life (*Alvarez et al.,* 1980; *Silver and Schultz,* 1982; *McLaren and Goodfellow,* 1990; *Sharpton and Ward,* 1990; *Ryder et al.,* 1996; *Alvarez,* 1997). The giant crater produced by that collision has now been definitely identified, a structure [Chicxulub (Mexico)] at least 180 km across, completely buried under the younger sediments of Mexico's Yucatán Peninsula (*Hildebrand et al.,* 1991; *Sharpton et al.,* 1992; *Morgan et al.,* 1997). Active debates continue about how this catastrophic event actually produced the extinction and whether similar impacts have caused the other major and minor extinctions recorded in the geologic record.

Although the recognition of impact events and their effects on Earth has been marked by debate and controversy (e.g., *Dietz,* 1963; *Bucher,* 1963; *French,* 1968a, 1990b; *Sharpton and Grieve,* 1990; *Nicolaysen and Reimold,* 1990), there is no longer any need to demonstrate either the existence or the importance of such impact events. The young but maturing science of impact geology is turning toward



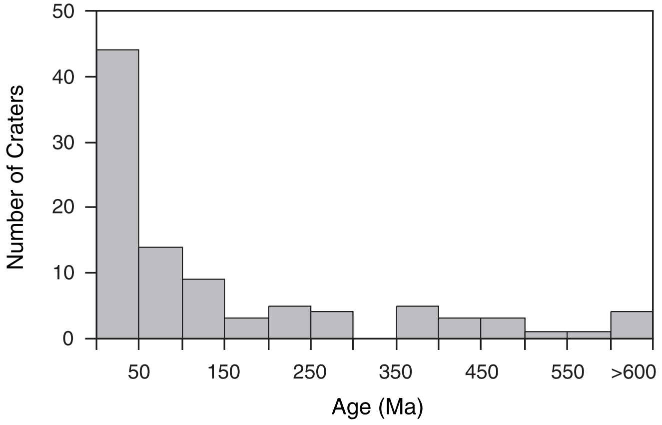


Fig. 1.2. Distribution of terrestrial impact structures. Locations of 145 currently known terrestrial impact structures (see *Grieve,* 1991; *Grieve et al.,* 1995; *Grieve and Pesonen,* 1996; *Koeberl and Anderson,* 1996b). The clearly nonrandom geographic distribution reflects geological and social factors rather than the original random bombardment flux: (1) increased preservation of impact structures on continental shield and cratonic areas that have been stable, and not deeply eroded, over long periods of time; (2) the restriction of past studies to continental areas, and a lack of systematic searches for submarine impact structures; (3) the active research and discoveries of particular workers, especially in Canada (*Beals et al.,* 1963; *Dence,* 1965; *Dence et al.,* 1968), Russia (*Masaitis et al.,* 1980) and Ukraine (*Gurov and Gurova,* 1991), Fennoscandia (*Pesonen,* 1996; *Pesonen and Henkel,* 1992), and Australia (*Glikson,* 1996b; *Shoemaker and Shoemaker,* 1996). The observed distributions of crater sizes and ages (inset) have been biased by postimpact geological processes; the ages of the great majority of preserved impact structures are <200 Ma, and small structures (0–5 km diameter) are greatly underrepresented. Diagram courtesy of V. L. Sharpton.

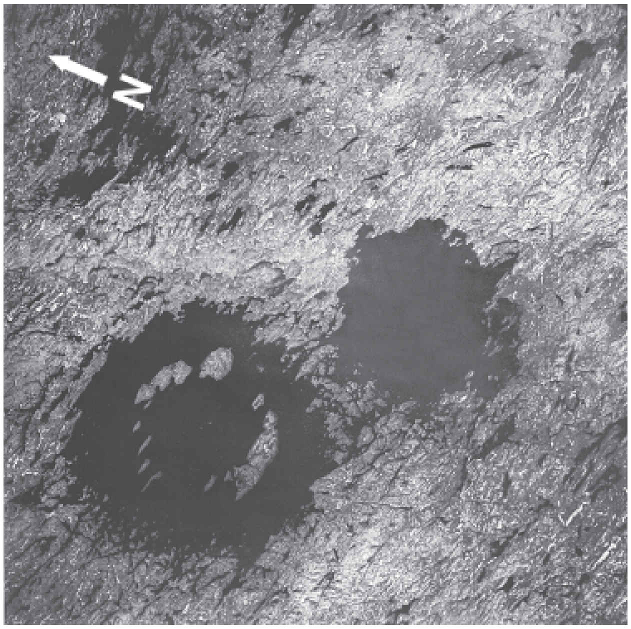


Fig. 1.3. Dual complex impact structures. Clearwater Lakes (Canada), two large, deeply eroded complex impact structures, both with central uplifts, were formed at ~290 Ma by an unusual double impact into the massive crystalline rocks of the Canadian Shield. In the larger structure, Clearwater Lake West (D = 32 km), the central uplift is expressed by a prominent ring of islands about 10 km in diameter; the islands are capped by units of breccias and impact melt. In the smaller Clearwater Lake East (D = 22 km), the central uplift is covered by the waters of the lake. Northeast is at the top of the picture. (STS 61A image 61A-35-86.)

new problems: finding the hundreds of undiscovered impact structures still preserved on Earth, discovering the full extent of impact effects on Earth, establishing the mechanisms by which large impacts produce geological and biological effects, understanding the puzzling chemical and mineralogical changes that occur in the extreme physical conditions of the impact environment, and using preserved terrestrial impact structures to better define the complex mechanics by which impact structures form on Earth and other planets.

1.2. THE PLANETARY PERSPECTIVE

The recognition of the importance of meteorite impacts on Earth has come largely from the study of other planets. Explorations of the Moon and the solar system by astronauts and robotic spacecraft in the 1960s and 1970s demonstrated that impact cratering has been, and still is, a major process in the origin and evolution of all the solid bodies of the solar system, from Mercury to the moons of Neptune (for summaries and references, see *Taylor,* 1982, Chapter 3; 1992, Chapter 4). The abundant craters on the surface of our Moon (Figs. 1.5 and 1.6) had been known for centuries since the time of Galileo, and their origin (either by impacts or volcanic activity) had been debated for just as long (for historical reviews, see *Hoyt,* 1987; *Mark,* 1987; *Wilhelms,* 1993). The Apollo program provided better views of the lunar surface, as well as samples returned by astronauts, and this combination gradually but definitely established the impact origin of most lunar craters (*Wilhelms et al.,* 1987; *Hörz et al.,* 1991; *Taylor,* 1992, Chapter 4).

Beyond the Moon, spacecraft revealed impact craters on every solid planetary surface that we could see: the other terrestrial planets Mercury, Venus (Fig. 1.7), and Mars (Figs. 1.8 and 1.9); the satellites of the gas-giant planets in the outer solar system (Figs. 1.10 and 1.11); and even small asteroids (Fig. 1.12).

The general acceptance of lunar and planetary craters as the results of impact events (*Taylor,* 1982, Chapter 3; 1992, Chapter 4) was based on several lines of evidence: their abundance on all solid planetary surfaces, their occurrence on objects of greatly differing composition (rocky, icy) and on surfaces of varying ages, the wide range of crater sizes ob-

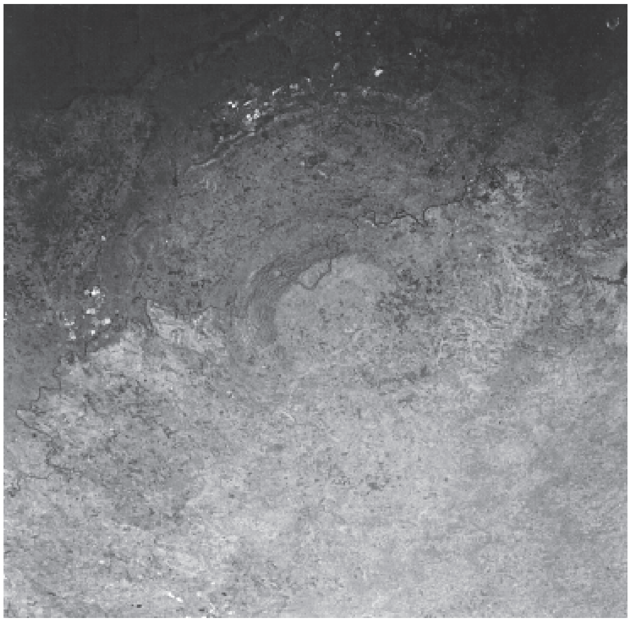


Fig. 1.4. A giant impact structure. One of the largest known terrestrial impact structures, Vredefort (South Africa) is located in the center of the Witwatersrand Basin, about 100 km from Johannesburg. With an age of nearly 2 Ga, the structure has been so deeply eroded that only subcrater rocks are still exposed, and the southern half of the structure has been covered by younger sediments. The structure now appears as a central core of uplifted ancient granitic rocks about 40 km in diameter (circular light-colored area in center), surrounded by a collar of upturned younger sediments and basalt lavas. This raised central core and collar rocks, about 80 km in diameter, is now believed to be only the central part of an impact structure originally 200–300 km in diameter. Despite the great age and deep erosion, the impact origin of Vredefort has been definitely established by a variety of preserved shock-metamorphic effects: shatter cones, planar deformation features in quartz, and the high-pressure minerals coesite and stishovite. North is approximately at the top. (STS 8 image 08-35-1294.)

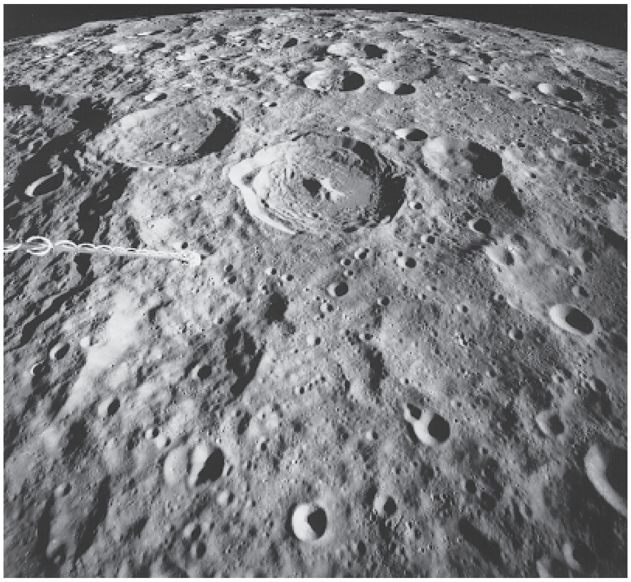


Fig. 1.5. Heavily cratered lunar highlands. The light-colored highland regions of the Moon record an intense and ancient bombardment between about 4.5 Ga and 3.8 Ga. During this time, cratering rates were hundreds to thousands of times their present values, and the highland surfaces were saturated with large craters >10 km in diameter. This view of the farside highlands, looking south from the lunar equator, shows two large complex impact craters: Green (D = 90 km) (upper center) and Hartmann (D = 70 km) on its left. These two complex craters, which show typical central uplifts and collapsed terraces in the inner walls, are accompanied by large numbers of smaller craters. The crater Hartmann also cuts the rim of the older impact basin Mendeleev (D = 330 km), part of which can be seen at the left. The spiral-like rod at left center is an instrument boom on the Apollo 16 spacecraft, from which this orbital picture was taken. (Apollo 16 image AS16-M-2370.)

served (from tiny microcraters <1 mm across on lunar rocks to great ringed basins >2000 km in diameter), their consistent and regular morphology, and their presence on tiny bodies (e.g., asteroids) too small to have ever generated internal volcanic activity.

The abundance of well-preserved impact craters on planetary surfaces of all kinds made it possible to use crater frequencies to determine relative geological ages, based on the simple principle that older surfaces accumulate more craters (*Shoemaker and Hackman,* 1962; *Shoemaker et al.,* 1963). On the Moon, where crater counts could be combined with absolute ages obtained by radiometric dating of returned samples, it became possible to estimate the flux of objects bombarding the Moon (and by implication, Earth as well) over geologic time by counting the craters of different sizes on surfaces of known age. However, application of the lunar data to other planets lacking absolute age data has been a complicated and problematic process (*Taylor,* 1992, Chapter 4).

Even before the Apollo program, it was recognized that the lunar bombardment rate had not been constant over time and that the ancient, heavily cratered lunar highlands record a bombardment rate thousands of times higher than that recorded by the younger maria (*Baldwin,* 1949, 1963). The Apollo data confirmed this conclusion and demonstrated that an intense bombardment of the Moon occurred between its formation (4.5 Ga) and about 3.8 Ga. The bombardment rate was most intense at about 4.5 Ga, decreased rapidly until about 3.8 Ga, and then leveled off (Fig. 1.13) (*Wilhelms et al.,* 1987; *Hörz et al.,* 1991; *Taylor,* 1992, Chapter 4). The bombardment rate after 3.8 Ga has been approximately constant (Fig. 1.13), although it has been suggested that variations of perhaps ±2× have occurred, especially during the Phanerozoic (<600 Ma).

It is now accepted that impact events, especially large ones, have had a major role in the formation and early history of the solar system and the solid objects in it. In current theories of solar system formation, the planets are believed to have formed by the steady accretion (with collisional impacts) of small objects (*planetesimals*) in an original solar nebula. But newer, post-Apollo theories suggest that large impact events, affecting nearly grown planets, may be responsible for many unexplained problems of planetary motions, compositions, and atmospheres (*Taylor,* 1992, Chapter 4). Many chemical and dynamical problems concerning the origin of the Moon are explained by the current theory that the Moon formed as the result of a collision be-

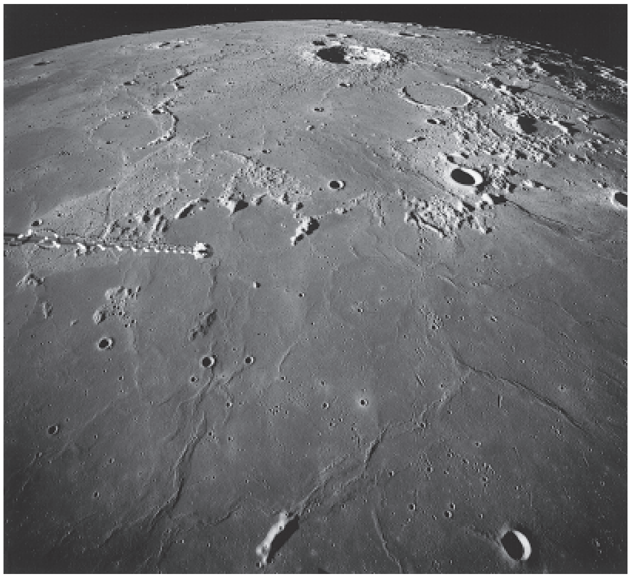


Fig. 1.6. Lightly cratered lunar maria. The much lower bombardment rate on the Moon since 3.8 Ga is clearly reflected in the lightly cratered character of these younger lava flows that fill the lunar maria in the lower half of this image. Craters are scattered and much smaller than those developed in highland areas. This view shows Mare Nubium in the south-central part of the Moon's nearside. The dark lava flows exposed here are relatively young by lunar standards (about 3.2–3.5 Ga). Bullialdus, the large fresh complex crater near the horizon, is about 60 km in diameter. The spiral-like rod at left center is an instrument boom on the Apollo 16 spacecraft, from which this orbital picture was taken. (Apollo 16 image AS16-M-2492.)

Fig. 1.7. Complex impact craters on Venus. Large, well-preserved impact craters on the surface of Venus were revealed by the Magellan spacecraft, which used an imaging radar system to penetrate the planet's opaque atmosphere. In this "crater farm" area, three large, well-preserved impact structures have been produced on a low-relief, slightly fractured surface that may consist of basalt lava flows. The "colors" in this picture actually represent different degrees of surface roughness detected by Magellan's radar system; dark surfaces (the target surface and the crater interiors) are smooth, while lighter areas (crater ejecta blankets and linear fractures in the preimpact surface) are rougher. The three largest craters show features typical of complex impact structures: circular outlines, complex central uplifts, and surrounding deposits of lobate ejecta. Aglaonice, the largest crater (center right), is 63 km in diameter. (Magellan image JPL P-36711.)

tween a Mars-sized object and the larger proto-Earth at about 4.5 Ga (*Hartmann et al.,* 1986). Similar impacts may have stripped off the silicate mantle of the planet Mercury, leaving the present iron-rich object (*Benz et al.,* 1988), may have removed the early primordial atmospheres of the planets (*Melosh and Vickery,* 1989; *Ahrens,* 1993), and may be responsible for the fact that Uranus' axis of rotation is tilted more than 90° from the axes of all the other planets. In considering the early solar system, large random impact events have become the method of choice for explaining planetary anomalies, a situation that provides local explanations but makes it more difficult to construct uniform theories for planetary development (*Taylor,* 1992; Chapter 4).

The planetary perspective is a critical part of the study of terrestrial impact structures. The widespread existence of impact craters throughout the solar system demonstrates that they must have been equally abundant on Earth, and the cratered surfaces of other planets make it possible to estimate the intensity and the effects of impact cratering on Earth. More important, impact craters on Earth and other planets complement each other. On other planets, where erosion and tectonics have not been extensive, we can see the preserved upper levels of craters, the sharply circular form, the widespread ejecta deposits, the lava-like bodies of impact melt, and the cliffs and terraces formed during crater development (Figs. 1.5, 1.7, and 1.8).

In most exposed terrestrial impact structures, such surface features have been removed by erosion, and the present surface exposes deeper levels within or even beneath the original crater. Terrestrial structures thus provide a unique third dimension to cratering studies, and their accessibility makes possible a wide range of investigations not possible on other planets. Terrestrial impact structures can be mapped, sampled, drilled, and analyzed in great detail, and they have provided critical "ground truth" for understanding impact phenomena on other planets. Many fundamental concepts of cratering mechanics — crater modification, central uplifts, impact melt formation and emplacement — have been established on terrestrial structures (*Shoemaker,* 1963; *Dence,* 1968, 1971; *Milton et al.,* 1972; *Dence et al.,* 1977; *Grieve et al.,* 1977, 1981; *Grieve and Cintala,* 1981, 1992) and then applied to craters elsewhere in the solar system (e.g., *Cintala and Grieve,* 1998).

1.3. A PECULIAR PROCESS: WHY IMPACTS ARE DIFFERENT

Large impact events differ in many ways from more familiar geological processes like volcanic explosions, earthquakes, and the slow movements of plate tectonics. Much of

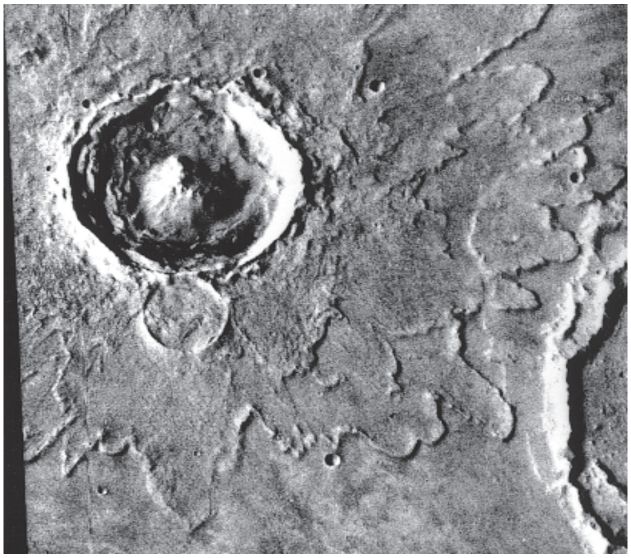


Fig. 1.8. A complex impact crater on Mars. This young complex crater (Yuty: D = 19 km) shows typical features: a circular outline, highly terraced interior walls, an unusually pronounced central peak, and a surrounding blanket of highly lobate ejecta. The complex appearance of the ejecta blanket suggests that it may have been partly fluidized by water melted from ice deposits within the target by the impact, and the exaggerated central peak may also reflect the existence of a lower-strength, volatile-bearing target. The thinness of the ejecta deposits is indicated by the fact that the small pre-Yuty crater just tangent to Yuty can still be distinguished through them. The arcuate structure at lower right is part of the wall of an older, larger crater. (Viking Orbiter image 003A07.)

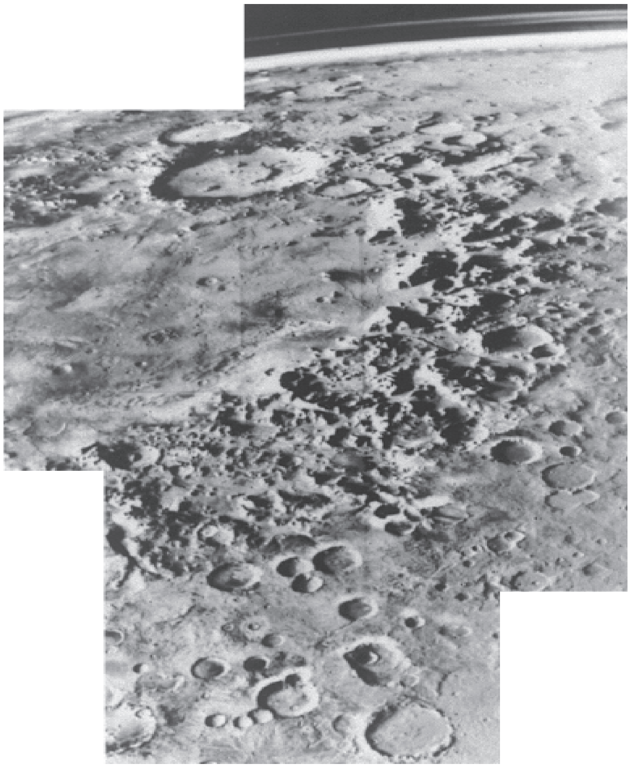


Fig. 1.9. An ancient multiring (?) impact basin on Mars. The flat-floored Argyre Basin (upper left) (D = 900 km) is apparently the youngest large impact basin recognized on Mars, but it is still an ancient and heavily eroded structure that has itself been struck by large projectiles since it formed (e.g., the large crater cutting the basin rim at top). This orbital panorama shows the smooth floor deposits within the basin and the mountainous nature of the enclosing rim. Because of the high degree of erosion, the actual diameter of Argyre is uncertain; a minimum diameter of about 900 km is indicated by the rugged rim shown in this picture, but the existence of additional rings (with diameters of 540, 1140, and 1852 km) has been suggested. The white streaks above the horizon (upper right) are hazes in the thin martian atmosphere. (Viking Orbiter image JPL P-17022.)

Fig. 1.10. Impact craters on one of Saturn's moons. Like many moons of the outer planets, Dione (D = 1120 km) is a low-density object composed largely or completely of ices. The surfaces of Dione and many other moons show abundant impact craters as well as a variety of other terrain types that probably reflect different degrees of internal activity. One hemisphere of Dione (left) shows abundant, well-preserved impact craters, while the other hemisphere (right) shows wispy streaks that may reflect fracturing or the eruption of volatiles. The larger craters show typical complex-crater morphologies with central peaks and terraced walls, e.g., Dido (left center; D = 120 km) and Aeneas (top, near horizon; D = 155 km). (Voyager 1 image JPL P-23101.)

the past confusion and controversy about meteorite impact on Earth has arisen from the fact that the chief features of large impact events are unfamiliar to geologists and the public alike.

1.3.1. Rarity

Unlike other geological processes, large meteorite impacts are rare, even over geological timescales, and there have been (fortunately) no historical examples of such events. For most people, the impact process involves only the occasional falls of small **meteorites,** which produce excitement and public interest, but only occasional minor damage. This lack of direct human experience with large impact events sets them apart from more familiar recurrent geological "catastrophes" such as floods, earthquakes, and volcanic eruptions and makes them harder to appreciate.

1.3.2. Immense Energy

Large impact events release energies that are almost incomprehensibly large by the more familiar standards of earthquakes and volcanic explosions. The energy of an impact event is derived from the **kinetic energy** of the impacting projectile and is equal to $1/2\ mv^2$, where m is the projectile mass and v its velocity. Because velocities of impacting objects are high, typically tens of kilometers per second, kinetic energies are also large, even for small objects (for details, see below and Table 2.1). An object only a few meters across carries the kinetic energy of an atomic bomb, and its impact could devastate a large city. Furthermore, unlike earthquakes and volcanic explosions, where the properties of Earth itself provide some upper bounds to the energy release, the impact energy is limited only by the mass and velocity of the projectile. The impact of an object only a few kilometers across (still smaller than many known asteroids and comets) can release more energy in seconds than the whole Earth releases (through volcanism, earthquakes, tectonic processes, and heat flow) in hundreds or thousands of years.

1.3.3. Instant Effects

Another critical difference between impacts and other geological processes is that the energy release in an impact event — and the formation of the resulting crater — is vir-

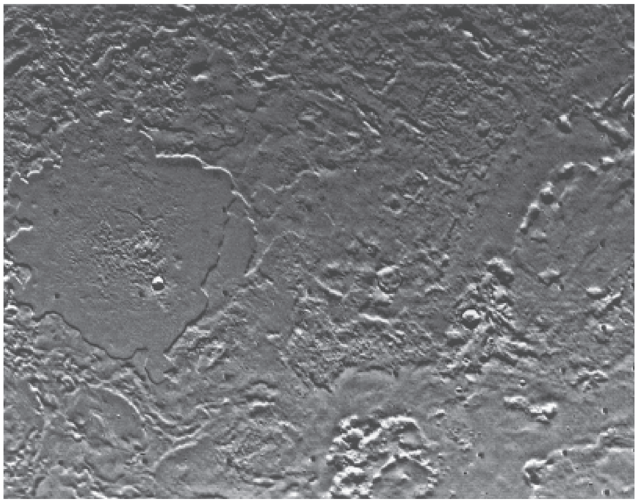


Fig. 1.11. Impact craters on a moon of Neptune. Triton, Neptune's largest moon (D = 2700 km), is now the most distant solid object in the solar system to be photographed at close range. When examined by the Voyager 2 spacecraft in 1989, Triton turned out to be an unexpectedly dense ice-rock world with a poorly understood geological history and a surface modified by ice deformation, possible melting and water flooding, erupting geysers of nitrogen, and strong winds. Despite this active and ongoing history, Triton's surface still preserves the results of meteorite bombardment. The large scalloped basin (left), about 200 km across, may represent a large impact structure subsequently modified by faulting, flooding, and filling with water ice. A sharp young impact crater about 15 km across has formed on the older surface, and other craters of similar size and sharpness are scattered across the region. The rarity of small, fresh, and young impact craters indicates that this part of Triton's surface is relatively young and has recently been modified by internal processes. (Voyager 2 image JPL P-34692.)

tually instantaneous. At the instant of impact, the object's kinetic energy is converted into intense high-pressure **shock waves,** which radiate rapidly outward from the impact point through the target rocks at velocities of a few kilometers per second (see e.g., *Melosh,* 1989, Chapters 3–5). Large volumes of target rock are shattered, deformed, melted, and even vaporized in a few seconds, and even large impact structures form in only minutes. A 1-km-diameter crater [about the size of Barringer Meteor Crater (Arizona)] forms in a few seconds. A 200-km-diameter structure [like Sudbury (Canada) or Vredefort (South Africa)] forms in less than 10 minutes, although subsequent geological adjustments, largely driven by gravity, will continue for many years.

1.3.4. Concentrated Energy Release

Most forms of internal terrestrial energy (heat flow, seismic waves) are released over large areas that are subcontinental to global in extent. By contrast, the energy of an impact event is released instantly, at virtually a single point on Earth's surface. Most of the energy passes, directly and rapidly, into the near-surface target rocks, the atmosphere, and the biosphere, where it can produce immediate and catastrophic changes.

A small impact, releasing the energy of only a few million tons of TNT (approximately the amount released by a hydrogen bomb), is similar in total energy to a severe earthquake or volcanic explosion, and its effects will be largely local (e.g., *Kring,* 1997). But a large impact transmits so much energy into the target that an impact structure tens or hundreds of kilometers in diameter is formed, accompanied by catastrophic environmental effects on a continental or global scale.

The near-surface release of impact energy, and the transfer of much of the energy directly into the biosphere, makes large impact events especially effective in causing devastating and widespread biological extinctions. Current impact-related models for the major Cretaceous-Tertiary (K/T) extinction (e.g., *Silver and Schultz,* 1982; *Sharpton and Ward,* 1990; *Kring,* 1993; *Ryder et al.,* 1996) indicate that, during the impact that formed the Chicxulub crater at 65 Ma, as much as 25–50% of the projectile's original kinetic energy was converted into heat. This heat not only vaporized the projectile itself, but also melted and vaporized large volumes of the near-surface sedimentary target rocks, releasing large amounts of CO_2 (from carbonates) and SO_2 (from evaporites). Introduced into Earth's atmosphere, together with large quantities of impact-produced dust, these gases and their reaction products could produce major environmental effects: immediate darkening and cooling, subsequent global warming, and deluges of acid rain. Any of these consequences, or a combination of them, could have produced the resulting widespread extinction.

Fig. 1.12. Impact craters on an asteroid. The small asteroids that produce impact craters on the larger planets and moons have themselves been bombarded by larger and smaller objects. Larger collisions can break asteroids apart, leaving irregular objects such as Gaspra (which has dimensions of about 19 × 12 × 11 km), shown in this flyby image taken by the Galileo spacecraft in 1991. Smaller collisions leave surviving asteroids covered with large and small craters; the largest craters shown here on Gaspra are 1–2 km across. (Galileo image JPL P-40450-C.)

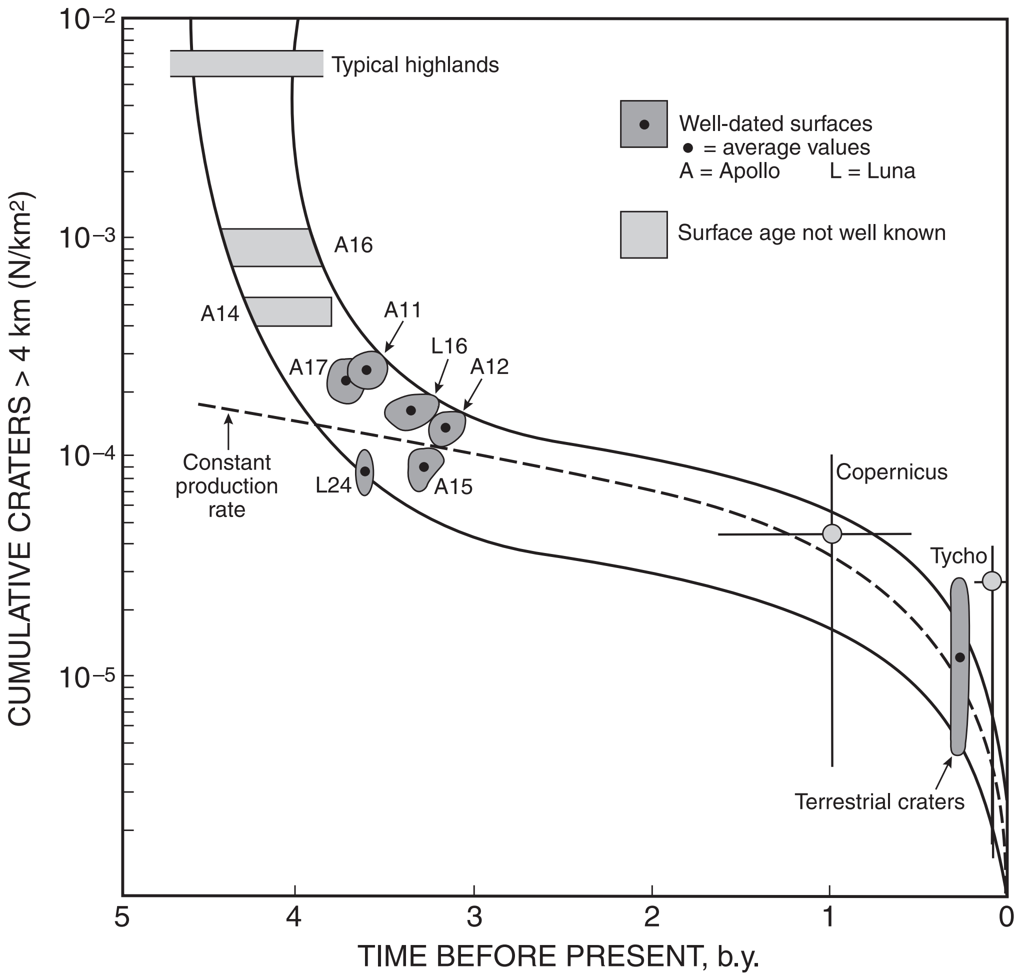


Fig. 1.13. Bombardment rates and crater formation during geologic time. This graph summarizes the results of studies in which the highly variable numbers of craters present on different lunar surfaces have been used to reconstruct the meteorite bombardment rate within the Earth-Moon system during the last 4 b.y. Lunar crater densities [expressed as the total number (N) of craters with D > 4 km per square kilometer of surface] have been measured from spacecraft photographs of various highlands and maria surfaces whose ages have been determined from samples returned by the Apollo (A) and Russian robotic Luna (L) missions. The data (bounded by two solid lines that indicate estimated uncertainties) are most precise for the well-dated maria surfaces, which have ages of 3.7–3.2 Ga. Ages of the older highland surfaces are not as well determined, but it is clear that crater-production rates before 3.8 Ga were much higher (≥100×) than in more recent times. The much lower crater formation rate after 3.8 Ga is not statistically different from a constant value (dashed line); this rate is also consistent with values estimated from the small population of preserved terrestrial impact structures. Age values for the large lunar craters Copernicus (about 1 Ga) and Tycho (about 100 Ma) have been indirectly determined from Apollo samples collected elsewhere on the Moon. (From *Hörz et al.,* 1991, Fig. 4.15, p. 84.)

1.3.5. Extreme Physical Conditions

The mechanism by which impacts do their work — generation and transmission of intense shock waves through the target rocks — is also unfamiliar to many geologists. Under normal conditions, rocks in Earth's crust and upper mantle are subjected to static load pressures produced by the weight of overlying rocks. These pressures are less than a few **gigapascals (GPa)** (1 GPa, a standard unit of pressure, equals 10^4 bar or about 10^4 atm). Normal geological stresses within Earth generate relatively low strain rates (typically10^{-3}/s to 10^{-6}/s), and rocks either deform slowly at lower pressures or fracture at higher pressures when their yield strengths (a few GPa) are exceeded. The general tendency of terrestrial rocks to fracture when the pressure gets too high, thus releasing the pressure, limits the pressure buildup in ordinary geological processes (e.g., earthquakes) to a few GPa.

These "normal" conditions do not exist in impact events. The rapid release of large amounts of energy in such events puts too much sudden stress on the target rocks for them to respond in the normal way. Typical impact velocities of tens of kilometers per second far exceed the velocities of sound in the target rocks (typically 5–8 km/s). The resulting impact-produced shock waves travel through the target rocks at supersonic velocities, and they impose intense stresses on the rocks without giving them time to give way by normal deformation. In the shock-wave environment, transient pressures may exceed 500 GPa at the impact point and may be as high as 10–50 GPa throughout large volumes of the surrounding target rock. Transient strain rates may reach 10^4/s – 10^6/s, orders of magnitude higher than those in ordinary geological processes. At the higher shock pressures (≥60 GPa), shock-produced temperatures can exceed 2000°C, and rapid, large-scale melting occurs immediately after the shock wave has passed.

1.3.6. Unique Deformation Effects

The extreme physical conditions of pressure, temperature, and strain imposed by transient shock waves produce unique effects (e.g., mineral deformation, melting) in the rocks and mineral grains through which they pass. These **shock-metamorphic effects** are distinct from features produced by normal geological deformation, and they are now generally accepted as unique products of impact events (for reviews and references, see *French and Short,* 1968; *Stöffler,* 1972, 1974; *Stöffler and Langenhorst,* 1994; *Grieve et al.,* 1996).

Shock-metamorphic effects (or "shock effects") have been crucial in establishing the importance of extraterrestrial impact events. Preserved meteorites around an impact crater can provide definite evidence of an impact origin, but only a small fraction of terrestrial impact structures (about a dozen) have actual preserved meteorites associated with them. These structures are all relatively small and geologically young. The Barringer Meteor Crater (Arizona), 1.2 km in diameter and about 50,000 years old (Fig. 1.1), is the largest member of this group.

The absence of meteorite fragments around older impact craters results from two causes: (1) the projectile itself is also subjected to the intense shock waves generated by the impact, and it is almost completely melted and vaporized; and (2) all meteorites are partly to completely composed of nickel-iron metal, and even surviving fragments of the projectile tend to be rapidly destroyed by surface weathering, except in the driest desert regions or on polar icecaps.

The rapid destruction of meteorites means that other lines of evidence must be used to identify older or deeply eroded terrestrial impact structures. Shock-metamorphic effects can be preserved in rocks for periods of 10^6–10^9 years, and they provide a unique means of identifying impact structures, especially ones that are old, deeply eroded, or both (*French and Short,* 1968). The great majority of currently known impact structures (currently over 150) have no preserved meteorites, but have been identified by the discovery of shock-metamorphic effects in their rocks (*Grieve,* 1991; *Grieve et al.,* 1995; *Grieve and Pesonen,* 1992, 1996).