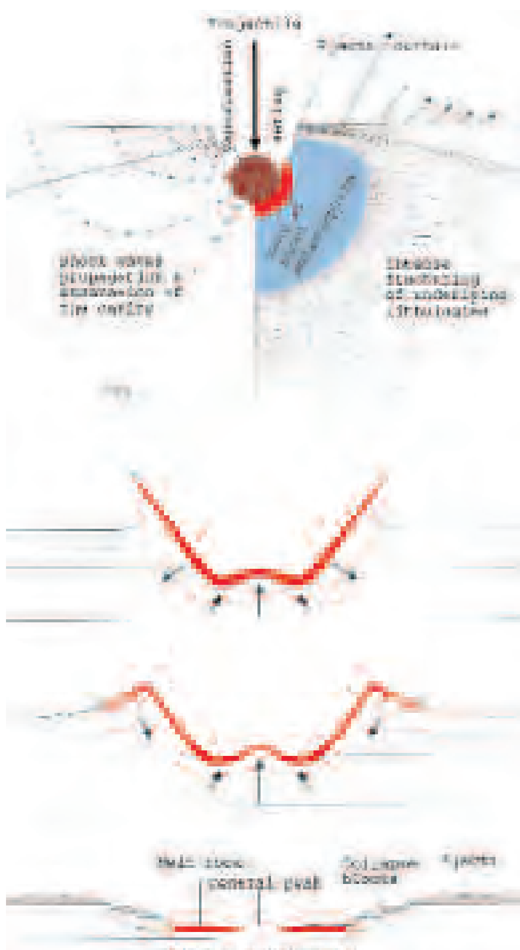
19 Asteroid and comet impacts on Earth

… les irréductible gaulois ne craignent qu'une chose que le ciel leur tombe sur la tête…
… the indomitable Gauls fear only one thing – that the sky will fall on their heads …
René Goscinny, Astérix le Gaulois/Asterix the Gaul, 1961

Collision is a major process in the evolution of planets, as attested by the 1994 crash of comet Shoemaker-Levy 9 on Jupiter. On solid planetary surfaces, these collisions result in topographical features called impact craters. Fresh craters are characterized by an almost perfect circular shape, as visible on the Moon. On Earth, the size of the approximately 170 known impact craters varies between a few tens of meters (Sikhote Alin, in the Russian Far East) to more than 180 km (112 miles; Chicxulub, off the coast of Yucatan, Mexico, p. 42). So far, no crater has been identified on the floor of the oceans.



Formation of a complex impact crater: the pressure of the shock waves expanding from the impact point is expressed in gigapascals (1 GPa = 10.000 bars). The excavation phase, when depth reaches to two time the projectile diameter, is followed by the rebound of the compressed underlying rocks and the collapse of the crater margin, leading to the final morphology.

Origin and frequency of impact craters

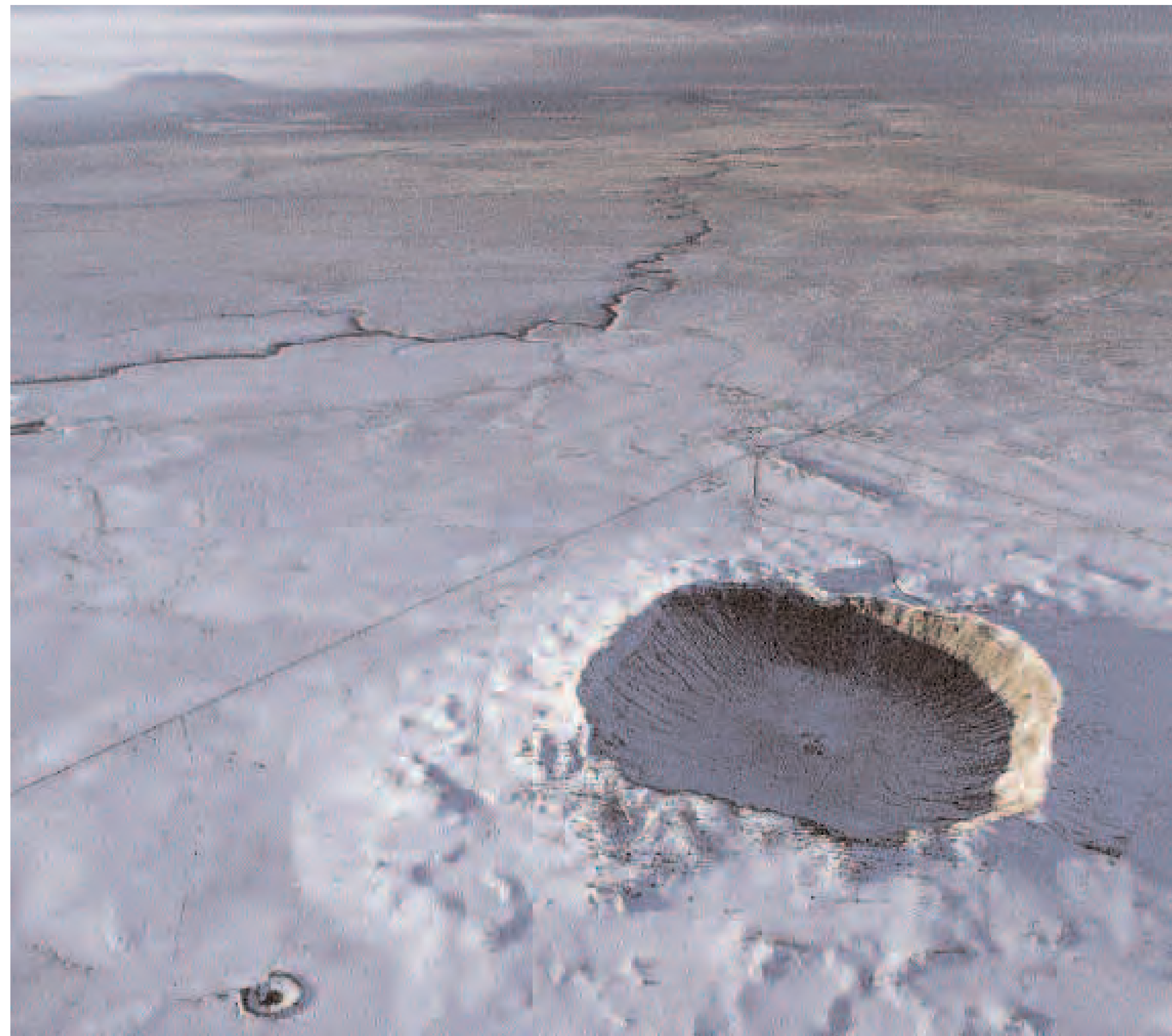
The formation of a crater by the impact of an object at hypervelocity is in fact a complex process comparable to nuclear explosions. The transformation of the projectile's kinetic energy releases a huge amount of energy ($=\frac{1}{2}mv^2$, where m and v are projectile's mass and velocity). The impact velocity, determined by celestial mechanics, ranges between 11 and 72 km per second: 11 km/s is the escape velocity of the Earth–Moon system and a body is simply accelerated to this speed by the planet's gravitational pull. The maximum speed for a comet (72 km/s) corresponds to the escape velocity of the solar system at a distance of 1 astronomical unit added to the Earth's orbital velocity (30 + 42 km/s).

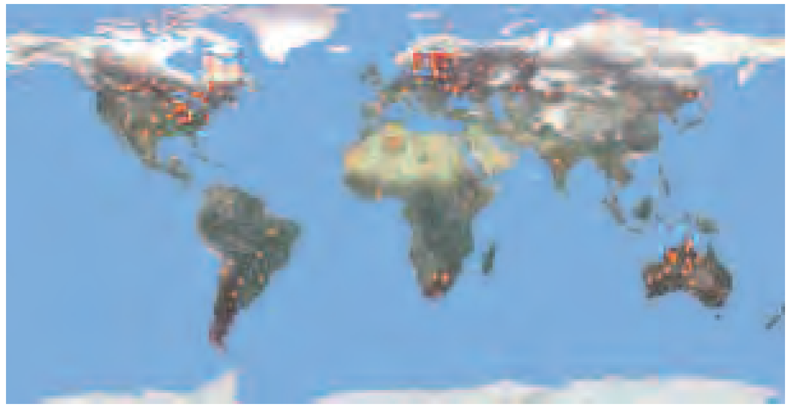
The impact of a 1.5-km (1-mile) object – smaller than most asteroids – releases the same amount of energy as the whole Earth in a year (from heat flow, earthquakes, tectonic activity, volcanism etc, combined). Asteroid or comet impacts have never been directly observed on Earth, despite possible speculations regarding mythologocial events. In 1908, an object around 50 m (165 ft) in diameter exploded several kilometres high in the atmosphere above Siberia. This 'Tunguska event' devastated more than 2,000 sq. km (772 sq. miles) of uninhabited forests. Such an explosion over a city would have wiped it off the map.

Morphology and formation of impact craters

On Earth, there is an approximate ratio of 1 to 20 between the size of the projectile and that of the resulting crater. A crater less than 4 km (2.5 miles) in diameter has a simple bowl-shape and a depth equivalent to ⅓ of its diameter. An elevated rim marks the crater edge and its inner flanks contain fractured and collapsed rocks. Above this size, a more complex crater forms: the concavity decreases (⅙ of its diameter) and uplift occurs in the central zone as the compressed rocks bounce back when the pressure is released. Much larger structures are composed of several elevated concentric rings. Multi-ring craters more than 1,000 km (620 miles) in size are known on the Moon, Mercury, Mars and Venus. The largest terrestrial craters – Chicxulub (65 million years old), Sudbury (Canada, *c.* 250 km/155 miles; 1,850 million years old) and Vredefort (South Africa, *c.* 300 km/186

The well-preserved Barringer crater (around 1.1 km/0.7 miles in diameter) in Arizona was formed some 50.000 years ago by the impact of an iron meteorite. The elevated rim is clearly visible.





Location of the known terrestrial impact craters. Most are found on old continental shields in the geologically well-studied regions of Europe, Canada, Australia and Russia while many remain to be discovered in South America, Asia and Africa

miles, 2,023 million years old) – also all probably belong to this category.

A crater forms by the propagation of intense shock waves at the collision point. These can reach velocities of over 10 km/s, and pressures equivalent to several million times atmospheric pressure. Their passage vaporizes, melts, deforms, compresses, fractures and pushes away large volumes of rocks, excavating a cavity in the process. In most cases, the projectile is completely vaporized and the upper layers of the target rock melt. Deeper in the rapidly evolving cavity, the rocks are displaced upwards with sufficient velocities to be ejected from the crater. A cloud of vapour, melt-particles and dust grows above the impact point, rising into the atmosphere like the mushroom cloud of a nuclear explosion.

Fragments of the target rocks are also expelled on more oblique trajectories as a curtain of ejecta that lands at a distance equivalent to several radii of the crater from the rim. The shock waves quickly lose energy as they spread out. When their velocity decreases to that of sound in rocks (5–8 km/s) they are transformed into seismic waves. Gravity and rock mechanics take over at this point, leading to the final crater morphology. A small crater forms in a few seconds, whereas a 100-km (62-mile) structure takes up to 10 minutes.

Such a process cannot be reproduced in the laboratory, and so our understanding of it is derived from theoretical calculations, experiments on the behaviour of shock waves in rocks, the study of mini-craters obtained by shooting at a variety of targets and field observations at preserved impact structures.

Identification and age of impact craters

Impact craters are usually recognized by the presence of topographic or geophysical anomalies. Seismic profiles outline the bowl-shape silhouette of the crater, allowing an estimate its size. Within a crater, the low-density fractured rocks induce a negative anomaly in the local gravity. A crater can also be unambiguously identified by the presence of a meteoritic component and/or shock-metamorphosed minerals. As a high-pressure shock wave passes through minerals, it irreversibly modifies their crystallographic structure, leading to the formation of typical and highly diagnostic microscopic defects. The only other process known to induce shock metamorphism in minerals is a nuclear explosion.

In rare cases, actual fragments of meteorites are preserved close to the crater (Barringer in Arizona). Otherwise, meteoritic contamination is detected by measuring higher than usual concentrations of elements in the platinum group, including iridium. Another approach is to use the isotopic ratios of osmium and chromium, which differ significantly in meteorites and the Earth's crust.

Outside the crater rim, the presence of tektites – impact glass – also represents evidence of an event. Impact glass can be differentiated from volcanic glass by its low water content and chemical

South Pole of the Moon showing multiple well-rounded craters; only the few projectiles hitting the planet surface at an angle less than 10º will produce an elongated crater. Several craters are larger than 1,000 km (620 miles). The lunar stratigraphy is based on the crater record.

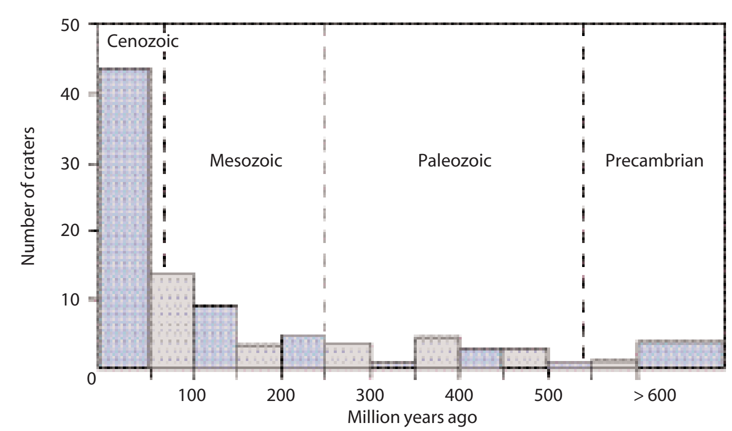
Projectile diameter	Impact frequency (1 event per)	Examples & released energy (equivalent TNT)
< 50 m (< 165 ft)	Detection frequent	Burns in atmosphere
50 m (165 ft)	200 to 400 years	Tunguska, *c.*12 megatons
100 m (328 ft)	1000 to 5000 years	Wolf Creek, Pretoria, Barringer, *c.* 15 megatons,
500 m (1,640 ft)	0.1 to 0.5 million years	Zhamanshin, Bosumtwi, Mien, *c.* $11x10^3$ megatons
1 km (0.6 miles)	1 million years	Ries, Rochechouart, *c.* $9x10^4$ megatons
5 km (3 miles)	10 to 50 million years	Popigai, Manicouagan, *c.* $1x10^7$ megatons
10 km (6 miles)	100 to 500 million years	Chicxulub, Sudbury, Vredefort, *c.* $1x10^8$ megatons
> 10 km (> 6 miles)	Probable?	Precambrian ejecta in Australia & Africa?
> 1,000 km (> 620 miles)	At least 1	Origin of the Moon

Estimated frequency of the impact of asteroids or comets on the Earth based on scaling up the occurrence of very small objects (micrometeorites) commonly falling through the atmosphere and crater counts and ages on the Earth and the Moon.

composition, reflecting the melting of the rocks. Tektites are small (about 1 cm/0.4 in), rounded or elongated glass particles ejected at high velocity from the crater and ultimately deposited over a vast geographic area, up to several thousand kilometres from their source, an effect known as a 'strewn field'. Four strewn fields are known from the Cainozoic (or Cenozoic, after 65 million years ago and still ongoing). One, the central European (*c.* 15 million years old), was ejected by the Ries impact in Bavaria all the way to the Czech Republic; the most recent is the Australasian (*c.* 0.7 million years old), extending all over the Indian ocean – the source crater remains unknown.

Most craters are younger than 250 million years. Small structures (less than 5 km/3 miles) erode rapidly and have largely disappeared, except very recent ones. Geological processes quickly erase the traces of ancient impacts, although the large Sudbury and Vredefort craters are Precambrian in age. Ejecta deposits are also difficult to identify in ancient sediments, except at the Cretaceous–Tertiary boundary. However, thick Precambrian ejecta layers occur in South Africa and West Australia, aged between 2.64 and 3.46 billion years old. Some of these layers may have been formed by projectiles larger than 20 km (12 miles) in diameter – twice the size of the one responsible for the dinosaurs' extinction. It is thus plausible to speculate that these very ancient periods of Earth history were marked by a higher occurrence of large extraterrestrial objects on Earth. Indeed, some 4.5 billion years ago, the Moon formed by a gigantic impact between the young Earth and an object the size of Mars.

Impacts of small and large objects on Earth will continue from the asteroid belt between Mars and Jupiter as well as a large number of 'Near Earth Objects' on orbits that can potentially intersect that of the Earth; comets also pose a latent menace. Constant monitoring of all these rogue bodies is an absolute necessity.



Distribution of known impact craters in the terrestrial geological record. The bias is clearly towards younger structures due to the rapid obliteration of old ones by geological processes such as plate tectonics, erosion and sedimentation.