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Cross-references

Albedo
 Asteroid Impact
 Asteroid Impact Mitigation
 Asteroid Impact Prediction
 Torino Scale

ASTEROID IMPACT

Christian Koeberl
 Natural History Museum, Vienna, Austria
 Center for Earth Sciences, University of Vienna,
 Vienna, Austria

Definition and introduction

Craters are a fundamental and common topographic form on the surfaces of planets, satellites, and asteroids. On large planetary bodies, of the size of the Moon and larger, craters can form in a variety of processes, including volcanism, impact, subsidence, secondary impact, and collapse. On smaller bodies (e.g., of the size of minor planets), impact may be the only process that can form craters. In the explanation of terrestrial crater-like structures, the interpretation as volcanic features and related structures (such as calderas, maars, cinder cones) has traditionally dominated over impact-related interpretations. The importance of impact cratering on terrestrial planets (Mercury, Venus, Mars), our Moon, and the satellites of the outer planets is obvious from the abundance of craters on their surfaces. On most bodies of the Solar System that have a solid surface, impact cratering is the most important surface-modifying process even today. On Earth, active geological processes rapidly obliterate the cratering record. To date only about 180 impact structures have been recognized on the Earth's surface. They come in various forms, shapes, and sizes, from 300 km to less than 100 m in diameter, and from recent to 2 billion years in age.

On the Moon and other planetary bodies that lack an appreciable atmosphere, it is usually easy to recognize impact craters on the basis of morphological characteristics. On the Earth, complications arise as a consequence of the obliteration, deformation, or burial of impact craters. Thus, it is ironic that despite the fact that impact craters on Earth can be studied directly in the field, they may be much more difficult to recognize than on other planets. Thus, the following diagnostic criteria for the

identification and confirmation of impact structures on Earth were developed: (a) crater morphology, (b) geophysical anomalies, (c) evidence for shock metamorphism, and (d) the presence of meteorites or geochemical evidence for traces of the meteoritic projectile – of which only (c) and (d) can provide confirming evidence. Remote sensing, including morphological observations, as well as geophysical studies, cannot provide confirming evidence – which requires the study of actual rock samples.

Impacts influenced the geological and biological evolution of our own planet; the best known example is the link between the 200-km-diameter Chicxulub impact structure in Mexico and the Cretaceous-Tertiary boundary. Understanding impact structures, their formation processes, and their consequences should be of interest not only to Earth and planetary scientists, but also to society in general.

History of impact cratering studies

In the geological sciences, it has only recently been recognized how important the process of impact cratering is on a planetary scale. During the last few decades, planetary scientists and astronomers have demonstrated that our Moon, Mercury, Venus, Mars, the asteroids, and the moons of the outer gas planets are all covered (some surfaces to saturation) with meteorite impact craters (Figure 1). However, it is fairly recent that this observation has become accepted among astronomers and geologists, because up to the first third of the twentieth century, it was commonly accepted that all lunar craters are of volcanic origin (and at that time the presence of craters on planetary bodies other than the moon had not yet been established).

The origin of craters on the Moon was discussed since 1610, when Galileo Galilei first discovered them. Geologists paid no interest to the Moon for the following centuries, so that the discussion of lunar craters was left to the astronomers. One of the earliest researchers to speculate about the origin of lunar craters was Robert Hooke in 1665, who proposed two alternative hypotheses. First, he dropped solid objects into a mixture of clay and water and found that these experiments resulted in crater-like features. However, he rejected the possibility that the lunar craters could have formed by such “impact” processes, because it was not clear from “whence those bodies should come,” as the interplanetary space was, at that time, considered to be empty. After all, Hooke made his experiments 135 years before the first asteroid, Ceres, was discovered by Piazzi in Palermo. Thus, he preferred a second hypothesis, in which, from experiments with “boiled alabaster,” he concluded that the lunar craters formed by some kind of gas – rejecting a perfectly correct explanation because the “boundary conditions” were missing.

The eighteenth and nineteenth centuries were dominated by the volcanic theory, and only a few researchers at the end of the nineteenth century expressed the idea that



Asteroid Impact, Figure 1 The full moon, showing the large circular impact basins that are the remnants of large impacts during the late heavy bombardment (about 4 billion years ago); photo by the Galileo spacecraft (NASA).

impacts might form craters (on the moon and elsewhere). For example, at the end of the nineteenth century, in 1892, Grove Karl Gilbert, chief geologist of the US Geological Survey, concluded – partly based on experiments made in his hotel room during a lecture tour – that the formation of lunar craters can be best explained by the impact theory. In contrast, he rejected the hypothesis that Meteor Crater in Arizona was formed by impact. This was odd because fragments of iron meteorites were actually found around this crater.

Real progress was only made in the first decades of the twentieth century, when the mining engineer Daniel Moreau Barringer (1860–1929) studied the “Coon Butte” or “Crater Mountain” structure (as the “Meteor Crater” was then called) in Central Arizona. Despite the opinion of several leading geologists (including Gilbert) that this structure was of volcanic origin, and that the presence of the meteorite fragments was only a coincidence, Barringer was convinced that this was an impact crater, and his work laid the foundations for a wider acceptance of the existence of impact craters on Earth.

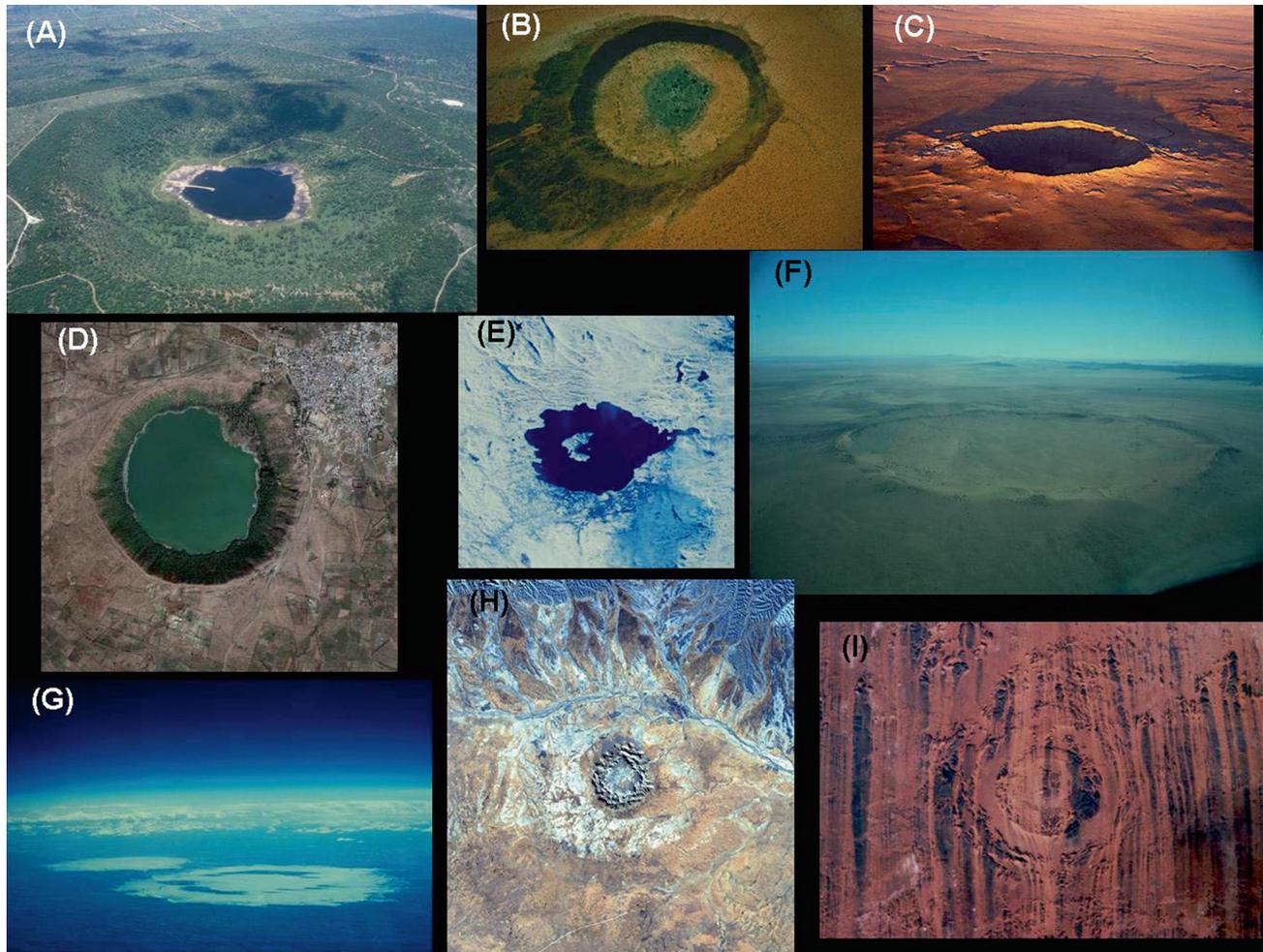
A well-known case in point is the Cretaceous-Tertiary (K-T) boundary, where the discovery of an extraterrestrial signature (Alvarez et al., 1980), together with the presence of shocked minerals (Bohor et al., 1984), led not only to the identification of an impact event as the cause of the end-Cretaceous mass extinction (Smit, 1999), but also to the discovery of a large buried impact structure about 200 km in diameter, the Chicxulub structure. Earlier, the idea that an extraterrestrial object would have influenced

the geological and biological evolution on the Earth was not even seriously considered. This might explain the mixture of disbelief, rejection, and ridicule with which the suggestion was greeted that an asteroid or comet impact wiped out the dinosaurs and other species at the end of the Cretaceous. It was the debate that followed this suggestion, which, over the past 20–30 years, finally led to a more general realization that impact cratering is an important process on the Earth as well (Figure 2), and not only on the other planetary bodies of the Solar System.

Formation of impact craters

Impact cratering is a high-energy event that occurs at more or less irregular intervals (although over long periods of time, an average cratering rate can be established). Part of the problem regarding recognition of the remnants of impact events is the fact that terrestrial processes (weathering, plate tectonics, etc.) either cover or erase the surface expression of impact structures on Earth. Many impact structures are covered by younger (i.e., post-impact) sediments and are not visible on the surface. Others were mostly destroyed by erosion. In some cases, the ejecta have been found far from any possible impact structure. The study of these ejecta led, in turn, to the discovery of some impact craters.

Before discussing the detailed mineralogical, petrographic, and geochemical characteristics of impact craters, it is important to give a short overview of their formation, criteria of recognition, and their general geology. From the morphological point of view, it is necessary to distinguish between an impact *crater*, that is, the feature that results from the impact, and an impact *structure*, which is what is observed today, that is, long after formation and modification of the crater. On Earth, two distinctly different morphological forms are known: *simple* craters (small bowl-shaped craters) with diameters of up to ≤ 2 –4 km, and *complex* craters, which are larger and have diameters of ≥ 2 –4 km (the exact changeover diameter between simple and complex crater depends on the composition of the target). Complex craters are characterized by a peak or peak ring that consists of rocks that are uplifted from greater depth and would not normally be exposed on the surface. The stratigraphic uplift amounts to about 0.1 of the crater diameter (e.g., Melosh, 1989). Craters of both types have an outer rim and are filled by a mixture of fallback ejecta and material slumped in from the walls and crater rim during the early phases of formation. Such crater infill may include brecciated and/or fractured rocks, and impact melt rocks. Fresh simple craters have an apparent depth (measured from the crater rim to present-day crater floor) that is about one third of the crater diameter, whereas that value for complex craters is closer to one sixth. On Earth basically all small craters are relatively young, because erosional processes obliterate small (0.5–10 km diameter) craters after a few million years, causing a severe deficit of such small craters.



Asteroid Impact, Figure 2 Examples of simple and complex impact craters on Earth. Craters in the upper row, and the one in the center row on the right, are simple craters, and the others are complex craters. Upper row: (a) Tswaing (Saltpan)-crater in South Africa (1.2 km diameter, 250,000 years old); (b) Wolfe Creek crater in Australia (1 km diameter, 1 Ma old); (c) Meteor Crater in Arizona, USA (1.2 km diameter, 50,000 years old); Center row: (d) Lonar crater, India (1.8 km diameter, age ca. 50,000 years); (e) Mistastin crater in Canada (28 km diameter, age ca. 38 Ma); (f) Roter Kamm crater in Namibia (2.5 km diameter, age ca. 4 Ma); bottom row: (g) Clearwater-double crater in Canada (24 and 32 km diameter, age ca. 250 Ma); (h) Gosses Bluff crater in Australia (24 km diameter, age 143 Ma); and (i) Aorounga crater in Chad (18 km diameter, age unknown but younger than ca. 300 Ma).

The formation of a crater by hypervelocity impact is – not only in geological terms – a very rapid process that is customarily divided into three stages: (1) contact/compression stage, (2) excavation stage, and (3) post-impact crater modification stage. For more detailed discussions of the physical principles of impact crater formation, the interested reader is referred to the literature (e.g., Melosh, 1989, and references therein). The most important aspect of impact cratering concerns the release of large amounts of kinetic energy (equal to $\frac{1}{2}mv^2$, m = mass, v = velocity) when an extraterrestrial body hits the surface of the Earth with cosmic velocities (ranging from about 11–72 km/s). The physical processes that govern the formation of an impact crater are the result of the extremely high amounts of energy that are liberated almost instantaneously when

the projectile hits the ground. For example, a meteorite with a diameter of 250 m has a kinetic energy that is roughly equivalent to about 1,000 mt of TNT, which would lead to the formation of a crater about 5 km in diameter. There is a difference between the behavior of a stony impactor and an iron one. Due to the difference in mechanical strength, smaller iron meteorites can reach the ground intact, in contrast to stony meteorites, which may undergo catastrophic disintegration in the atmosphere. The impact energy can be compared to that of “normal” terrestrial processes, such as volcanic eruptions or earthquakes. During a small impact event, which may lead to craters of 5–10 km in diameter, about 10^{24-25} ergs (10^{17-18} J) are released, comparable to the about 6.10^{23} ergs (6.10^{16} J) that were released over several months during

the 1980 eruption of Mount St. Helens (see, e.g., French, 1998). In the case of an impact, the kinetic energy is concentrated more or less at a point on the Earth's surface, leading to an enormous local energy increase.

Schematically, the formation of an impact crater can be summarized as follows: First, a relatively small extraterrestrial body, traveling at a velocity of several tens of kilometers per second, hits the surface; this marks the beginning of the contact and compression stage. Almost immediately, a small amount of material is ejected from the impact site during a process called jetting with velocities that can approach about one half of the impact velocity. The jetted material is strongly contaminated with projectile material. When the projectile hits the surface, a shock wave is propagated hemispherically into the ground. Because the pressures in the shock waves are so high, the release of the pressure (decompression) results in almost instantaneous melting and vaporization of the projectile – and of large amounts of target rocks. Results of the interaction of the shock wave with matter can be observed in various forms of shocked minerals and rocks, all of which originate during the contact (or compression) stage, which only lasts up to a few seconds even for large impacts. After the passage of the shock wave, the high pressure is released by a so-called rarefaction wave (also called release wave), which follows the shock front. The rarefaction wave is a pressure wave, not a shock wave, and travels at the speed of sound in the shocked material. The rarefaction wave leads to the creation of a mass flow that opens up the crater, marking the beginning of the excavation phase. Important changes in the rocks and minerals occur upon decompression, when the material follows a release adiabat in a pressure versus specific volume diagram. Excess heat appears in the decompressed material, which may result in phase changes (e.g., melting or vaporization).

The actual crater is excavated during this stage. Complex interactions between the shock wave(s) and the target, as well as the release wave(s), lead to an excavation flow. In the upper layers of the target, material moves mainly upward and out, whereas in lower levels material moves mainly down and outward, which results in a bowl-shaped depression, the *transient cavity*. This cavity grows in size as long as the shock and release waves are energetic enough to excavate material from the impact location. At this point a note of caution is necessary. For a crater about 200 km in diameter, the depth of the transient cavity can easily reach 60 km. However, only about one third of this is excavation, the rest is simply material that is pushed down. Thus, even the largest craters known on Earth have not resulted in excavation of mantle material, and impact-induced volcanism is implausible and has never been found. Afterward, gravity and rock-mechanical effects lead to a collapse of the steep and unstable rims of the transient cavity, and widening and filling of the crater. Compared to the contact stage, the excavation stage takes longer, but still only up to a minute or 2 even in large craters of more than 200 km diameter.

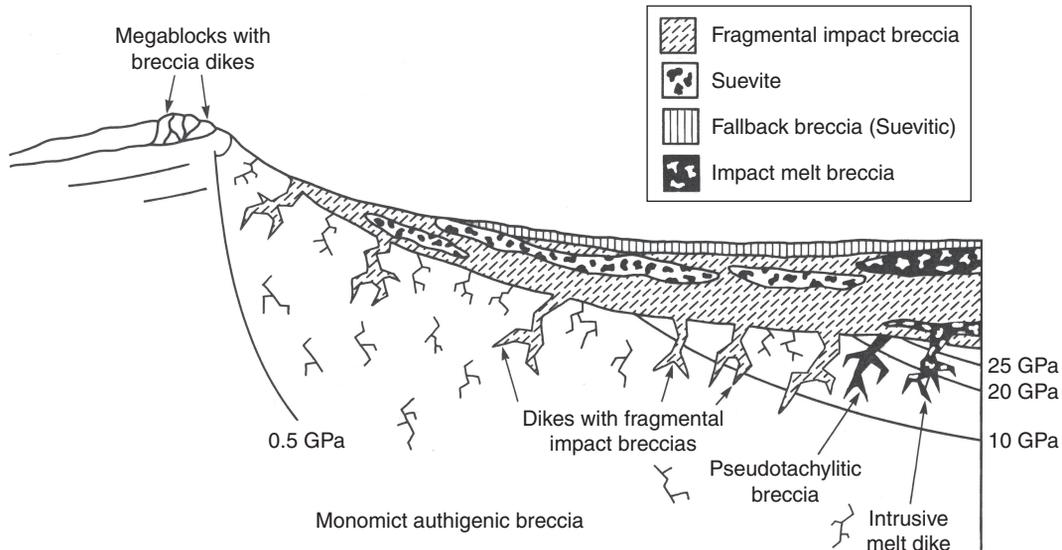
Details on the physics and mechanics of the formation of impact craters can be found in the publication by Melosh (1989).

Recognition criteria for an impact crater

The affected rocks are important witnesses for the characteristics of the impact process. As mentioned above, crater structures are filled with melted, shocked, and brecciated rocks (Figure 3). Some of these are in situ, and others have been transported, in some cases to considerable distances from the source crater. The latter are called ejecta. Some of that material can fall back directly into the crater, and most of the ejecta end up close to the crater (<5 crater radii; these are called *proximal* ejecta), but a small fraction may travel much greater distances and are then called *distal* ejecta. The book by Montanari and Koeberl (2000) contains more detailed information on impact ejecta (see also entry *Impact Ejecta*).

How to recognize an impact crater is an important topic. On the Moon and other planetary bodies that lack an appreciable atmosphere, impact craters can commonly be recognized from morphological characteristics, but on Earth complications arise as a consequence of the obliteration, deformation, or burial of impact craters. This problem made it necessary to develop diagnostic criteria for the identification and confirmation of impact structures on Earth (see French, 1998; French and Koeberl, 2010). The most important of these characteristics are as follows: (a) crater morphology, (b) geophysical anomalies, (c) evidence for shock metamorphism, and (d) the presence of meteorites or geochemical evidence for traces of the meteoritic projectile. Morphological and geophysical observations are important in providing supplementary (or initial) information. Geological structures with a circular outline that are located in places with no other obvious mechanism for producing near-circular features may be of impact origin and at least deserve further attention. Geophysical methods are also useful in identifying promising structures for further studies, especially in the case of subsurface features. In complex craters, the central uplift usually consists of dense basement rocks and usually contains severely shocked material. This uplift is often more resistant to erosion than the rest of the crater, and thus, in old eroded structures the central uplift may be the only remnant of the crater that can be identified. Geophysical characteristics of impact craters include gravity, magnetic properties, reflection and refraction seismics, electrical resistivity, and others (see Grieve and Pilkington, 1996, for a review).

Of the criteria mentioned above, only the presence of diagnostic shock metamorphic effects and, in some cases, the discovery of meteorites, or traces thereof, are generally accepted to provide unambiguous evidence for an impact origin. Shock deformation can be expressed in macroscopic form (shatter cones) or in microscopic form. The same two criteria apply to distal impact ejecta layers and allow to confirm that material found in such layers



Asteroid Impact, Figure 3 Cross-section through a hypothetical simple impact crater, showing the distribution of possible impact-derived materials and rock formations (After Koeberl, 2002).

originated in an impact event at a possibly still unknown location. As of 2010 about 180 impact structures have been identified on Earth based on these criteria.

Shock metamorphism

In nature, shock metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. The response of materials to shock has been the subject of study over much of the second half of the twentieth century, in part stimulated by military research. Using various techniques, controlled shock wave experiments, which allow the collection of shocked samples for further studies, have led to a good understanding of the conditions for the formation of shock metamorphic products and a pressure-temperature calibration of the effects of shock pressures up to about 100 GPa (see, e.g., French and Short, 1968; Stöffler and Langenhorst, 1994; Grieve et al., 1996; French and Koeberl, 2010; and references therein).

For the identification of meteorite impact structures, suevites and impact melt breccias (or impact melt rocks) are the most commonly studied units. It is easy to distinguish between the two impact formations, as suevites are polymict breccias that contain inclusions of melt rock (or impact glass) in a clastic groundmass, and impact melt breccias have a melt matrix with a variable amount of (often shocked) rock fragments as clasts (they are also referred to in the literature as “melt-matrix breccias”). Whether or not these various breccia types are present and/or preserved in a crater depends on factors including the size of the crater, the target composition (e.g., crystalline or sedimentary rocks), the degree of porosity of the target, and the level of erosion for an impact structure. In cases of very deeply eroded structures, only remnants of

injected impact breccias in the form of veins or dikes may remain. Besides injections of suevite and impact melt rock, and local (in situ) formations of monomict or polymict clastic impact breccia, this may involve veins and pods of so-called “pseudotachylitic breccia” that are recorded from a number of impact structures. This material may closely resemble what is known as “pseudotachylite,” the term for “friction melt.” However, it has become clear in recent years that not all of the formations of such appearance actually represent friction melt, but may also include impact melt rock and even tectonically produced fault breccias (friction melt, mylonite, or cataclasite).

The rocks in the crater rim zone are usually only subjected to relatively low shock pressures (commonly <2 GPa), leading mostly to fracturing and brecciation, and often do not show shock-characteristic deformation. Even at craters of several kilometers in diameter, crater rim rocks that are in situ rarely show evidence for shock deformation. However, there may be injections of impact breccias that may contain shock metamorphosed mineral and rock fragments. In well-preserved impact structures, the area directly outside the crater rim is covered by a (vertical) sequence of different impactite deposits, which often allow the identification of these structures as being of impact origin.

The presence of shock metamorphic effects constitutes confirming evidence for impact processes. In nature, shock metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. Shock metamorphic effects are best studied in the various breccia types that are found within and around a crater structure, as well as in the formations exhumed in the central uplift area. During the impact, shock pressures of about

≥ 100 GPa and temperatures $\geq 3,000^\circ\text{C}$ are produced in large volumes of target rock. These conditions are significantly different from conditions for endogenic metamorphism of crustal rocks, with maximum pressures of usually < 2 GPa and temperatures $< 1,200^\circ\text{C}$. Shock compression is not a thermodynamically reversible process, and most of the structural and phase changes in minerals and rocks are uniquely characteristic of the high pressures (diagnostic shock effects are known for the range from 8 to > 50 GPa) and extreme strain rates (10^6 – 10^8 s^{-1}) associated with impact. The products of static compression, as well as those of volcanic or tectonic processes, differ from those of shock metamorphism, because of lower peak pressures and strain rates that are different by many orders of magnitude.

A wide variety of microscopic shock metamorphic effects have been identified (see Table 1). The most common ones include planar microdeformation features; optical mosaicism; changes in refractive index, birefringence, and optical axis angle; isotropization (e.g., formation of diaplectic glasses); and phase changes (high-pressure phases; melting). Kink bands (mainly in micas) have also been described as a result of shock metamorphism, but can also be the result of normal tectonic deformation (for reviews and images of examples, refer to Stöffler and Langenhorst, 1994; Grieve et al., 1996; French, 1998; French and Koeberl, 2010).

Planar microstructures are the most characteristic expressions of shock metamorphism and occur as planar fractures (PFs) and planar deformation features (PDFs). The presence of PDFs in rock-forming minerals (e.g., quartz, feldspar, or olivine) provides diagnostic evidence for shock deformation, and thus, for the impact origin of

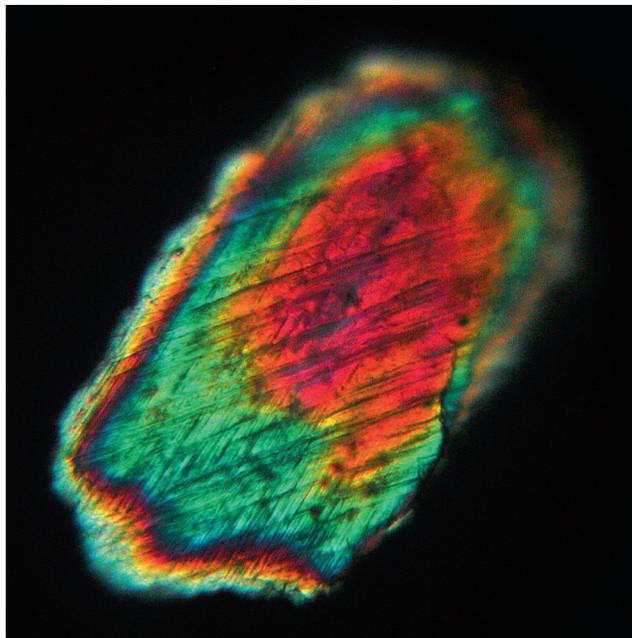
a geological structure or ejecta layer (see, e.g., Stöffler and Langenhorst, 1994; Montanari and Koeberl, 2000; French and Koeberl, 2010, and references therein). Good examples are shown in Figure 4. PFs, in contrast to irregular, non-planar fractures, are thin fissures, spaced about $20\ \mu\text{m}$ or more apart. While they are not considered shock diagnostic per se, should they be observed in significant abundance and particularly in densely spaced sets of multiple orientations, they can provide a strong indication of shock pressures around 5–10 GPa. To an inexperienced observer, it is not always easy to distinguish “true” PDFs from other lamellar features (fractures, fluid inclusion trails, tectonic deformation bands).

The most important characteristics of PDFs are that they are extremely narrow, closely and regularly spaced, completely straight, parallel, extend often (though not always) through a whole crystal, and, at shock pressures above about 15 GPa, occur in more than one set of specific crystallographic orientation per grain. This way, they can be distinguished from features that are produced at lower strain rates, such as the tectonically formed Böhm lamellae, which are not completely straight, occur only in one set, usually consist of bands that are $> 10\ \mu\text{m}$ wide, and are spaced at distances of $> 10\ \mu\text{m}$. Transmission electron microscopy (TEM) studies demonstrate that PDFs consist of amorphous silica, that is, they are planes of amorphous quartz that extend through the quartz crystal. This allows them to be preferentially etched by, for example, hydrofluoric acid, thus accentuating the planar deformation features. PDFs occur in planes that correspond to specific rational crystallographic orientations (for details, see, e.g., Stöffler and Langenhorst, 1994). With increasing shock pressure, the distances

Asteroid Impact, Table 1 Characteristics of shock deformation features in rocks and minerals

Pressure (GPa)	Features	Target characteristics	Feature characteristics
2–45	Shatter cones	Best developed in homogeneous fine-grained, massive rocks.	Conical fracture surfaces with subordinate striations radiating from a focal point.
5–45	Planar fractures and Planar deformation features (PDFs)	Highest abundance in crystalline rocks; found in many rock-forming minerals (e.g., quartz, feldspar, olivine, and zircon).	PDFs: Sets of extremely straight, sharply defined parallel lamellae; may occur in multiple sets with specific crystallographic orientations.
30–40	Diaplectic glass	Most important in quartz and feldspar (e.g., maskelynite from plagioclase)	Isotropization through solid-state transformation under preservation of crystal habit as well as primary defects and sometimes planar features. Index of refraction lower than in corresponding crystal but higher than in fusion glass.
15–50	High-pressure polymorphs	Quartz polymorphs most common: coesite, stishovite; but also ringwoodite from olivine, and others	Recognizable by crystal parameters, confirmed usually with XRD or NMR; abundance influenced by post-shock temperature and shock duration; stishovite is temperature-labile.
> 15	Impact diamonds	From carbon (graphite) present in target rocks; rare	Cubic (hexagonal?) form; usually very small but occasionally up to mm-size; inherits graphite crystal shape.
45– > 70	Mineral melts	Rock-forming minerals (e.g., lechatelierite from quartz)	Impact melts are either glassy (fusion glasses) or crystalline; of macroscopically homogeneous, but microscopically often heterogeneous composition.

XRD X-ray diffraction, NMR nuclear magnetic resonance, PDF planar deformation features
 Table after Montanari and Koeberl (2000)



Asteroid Impact, Figure 4 Shock-characteristic planar deformation features (PDFs) in a quartz grain (in distal ejecta from the Manson impact crater, found in South Dakota). Width of the grain ca. 100 μm . Multiple intersecting sets of PDFs are clearly visible.

between the planes decrease, and the PDFs become more closely spaced and more homogeneously distributed through the grain, until at about 30–35 GPa the grains show complete isotropization. Depending on the peak pressure, PDFs are observed in about 2–10 orientations per grain. To confirm the presence of PDFs, it is necessary to measure their crystallographic orientations by using either a universal stage or a spindle stage with an optical microscope, or to characterize them by TEM. Because PDFs are well developed in quartz (Stöffler and Langenhorst, 1994), a very widely observed rock-forming mineral, and because their crystallographic orientations are easy to measure in this mineral, most studies report only shock features in quartz. However, other rock-forming minerals, as well as accessory minerals, also develop PDFs.

Higher shock pressures than those recorded in PDFs in quartz and other rock-forming minerals lead to shock-induced amorphization (without melting) of the minerals (producing “diaplectic” minerals, such as diaplectic quartz or feldspar), thermal decomposition or melting of selected minerals (e.g., the monomineralic melt of quartz is lechatelierite), and whole-rock melting. Impact glasses can form directly at a crater, or be ejected to great distances (e.g., tektites). These melt rocks and glasses are often the objects of geochemical investigations. For example, the detection of small amounts of meteoritic matter in breccias and melt rocks can also provide confirming evidence of impact (Koeberl, 2007).

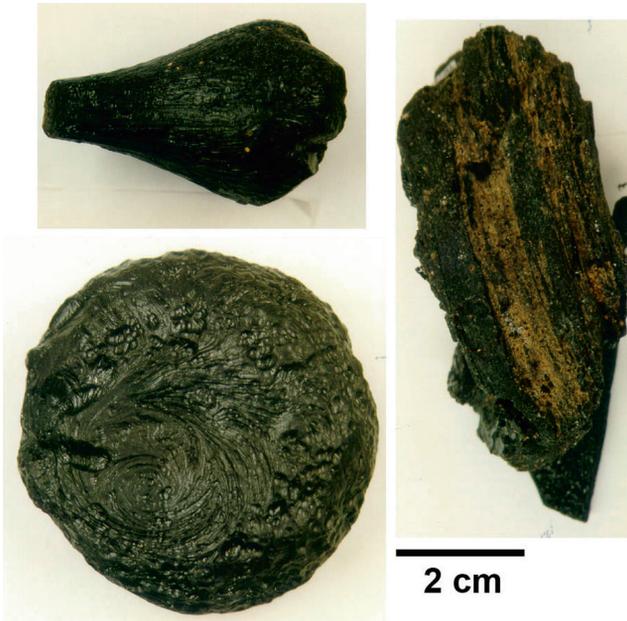
Tektites and microtektites

Tektites are chemically homogeneous, often spherically symmetric natural glasses, with most being a few centimeters in size (Figure 5). Mainly due to chemical studies, it is now commonly accepted that tektites are the product of melting and quenching of terrestrial rocks during hypervelocity impact on the Earth. The chemistry of tektites is in many respects identical to the composition of upper crustal material. Tektites are currently known to occur in four strewn fields of Cenozoic age on the surface of the Earth. Strewn fields can be defined as geographically extended areas over which tektite material is found. The four strewn fields are the North American, Central European (moldavite), Ivory Coast, and Australasian strewn fields. Tektites found within each strewn field have the same age and similar petrological, physical, and chemical properties. Relatively reliable links between craters and tektite strewn fields have been established between the Bosumtwi (Ghana), the Ries (Germany), and the Chesapeake Bay (USA) craters and the Ivory Coast, Central European, and North American fields, respectively. The source crater of the Australasian strewn field has not yet been identified. Tektites have been the subject of much study, but their discussion is beyond the scope of the present review. For details on tektites see the reviews by Koeberl (1994) and Montanari and Koeberl (2000).

In addition to the “classical” tektites on land, microtektites (<1 mm in diameter) from three of the four strewn fields have been found in deep-sea cores. Microtektites have been very important for defining the extent of the strewn fields, as well as for constraining the stratigraphic age of tektites, and to provide evidence regarding the location of possible source craters. Microtektites have been found together with melt fragments, high-pressure phases, and shocked minerals and, therefore, provide confirming evidence for the association of tektites with an impact event. The variation of the microtektite concentrations in deep-sea sediments with location increases toward the assumed or known impact location.

There has been some discussion about how to define a tektite, but the following characteristics should probably be included (see Koeberl, 1994; Montanari and Koeberl, 2000): (1) they are glassy (amorphous); (2) they are fairly homogeneous rock (not mineral) melts; (3) they contain abundant lechatelierite; (4) they occur in geographically extended strewn fields (not just at one or two closely related locations); (5) they are distal ejecta and do not occur directly in or around a source crater, or within typical impact lithologies (e.g., suevitic breccias, impact melt breccias); (6) they generally have low water contents and a very small extraterrestrial component; and (7) they seem to have formed from the uppermost layer of the target surface (see below).

An interesting group of tektites are the Muong Nong-type tektites, which, compared to “normal” (or splash-form) tektites are larger, more heterogeneous in



Asteroid Impact, Figure 5 Several Australasian tektites (from Thailand), showing the variety in shapes and forms. Tektites are distal impact ejecta, which formed by total melting of continental crustal target rocks.

composition, of irregular shape, have a layered structure, and show a much more restricted geographical distribution. They are also important because they contain relict mineral grains that indicate the nature of the parent material and contain shock-produced phases that indicate the conditions of formation. The occurrence of relict minerals in some tektites points to sedimentary source rocks. Muong Nong-type tektites contain unmelted relict inclusions, including zircon, chromite, quartz, rutile, and monazite, all showing evidence of various degrees of shock metamorphism. Coesite, stishovite, and shocked minerals were found in the North American and Australasian microtektite layers.

Despite knowing the source craters of three of the four tektite strewn fields, we still do not know exactly when and how during the impact process tektites form. Besides the characteristics mentioned above, tektites contain a relatively high amount of the cosmogenic isotope beryllium-10 (^{10}Be), which cannot have originated from direct irradiation with cosmic rays in space or on Earth, but can only have been introduced from sediments that have absorbed ^{10}Be that was produced in the terrestrial atmosphere. Tektites might be produced in the earliest stages of impact, which are poorly understood. It is clear, however, that tektites formed from the uppermost layers of terrestrial target material (otherwise they would not contain any ^{10}Be). However, the question of which process was responsible for tektite production and distribution remains the subject of further research.

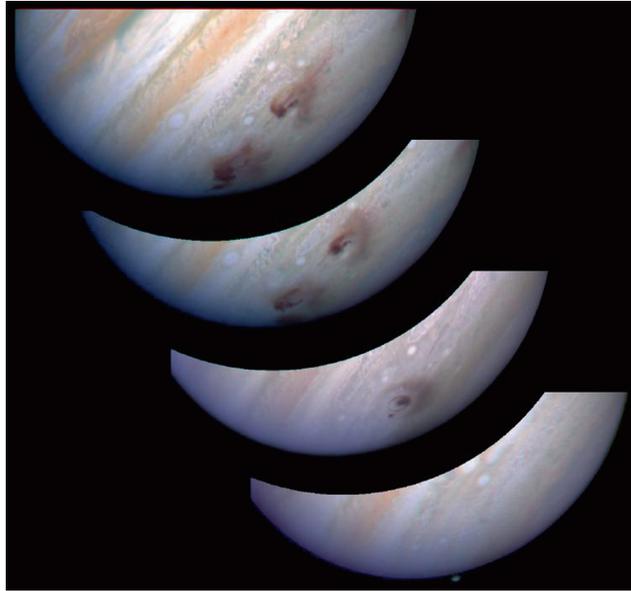
The hazards of asteroid impact

In July 1994, the fragments of comet Shoemaker-Levy 9 that crashed into the atmosphere of the planet Jupiter, producing impact plumes the size of our own planet (Figure 6), brought home to billions of people all over the world that impact catastrophes are not only a matter of the distant past but that they could happen any time, any place in the Solar System – also on Earth. And just about 100 years ago the Tunguska explosion of June 30, 1908, devastated some 2,000 km² of Siberian forests and caused environmental effects as far as London, and an air pressure signal around the world. Having been debated as the result of impact as much as of the explosion of a nuclear UFO, it is now widely accepted that this explosion was caused by the explosive disruption of a small (maybe 30–50 m wide) asteroid within the atmosphere, with an explosive energy of about 5–10 Mton TNT-equivalent.

Even more recently, a small cosmic projectile impacted in Peru on September 15, 2007. The Carancas meteorite created a ca. 14-m-wide impact crater, in a rather remote area of that country, and besides several people sustaining a significant scare, no casualties are known. However, even though this impact event was of insignificant size on a planetary scale (the largest impact structure known in the Solar System, the South Pole-Aitken basin in the south polar region of the Moon, measures some 2,500 km in diameter), there would have been hundreds of victims if this event had occurred in densely populated areas of our Planet. Clearly the understanding of impact processes is an important issue for mankind – especially if one considers what happened to the dinosaurs and their contemporaries 65 Ma ago. The impact of a 5–15-km asteroid at Chicxulub on the Yucatán peninsula generated then a 180 km diameter impact structure with global catastrophic effects (e.g., papers in Ryder et al. 1996).

The 1994 impact of fragments of comet Shoemaker-Levy 9 into the atmosphere of Jupiter demonstrated to humankind that impact is not a threat of the past. Hardly a year goes by without a call of danger from a “rogue asteroid” to Earth – although so far, all of them seem to have remained without cause. However, the terrestrial cratering record predicts a Tunguska event – impact of a roughly 50-m-sized projectile – for every 1,500 years or so, and if this event had occurred in a highly populated region, this relatively minor event comparable to ca. 1,000 Hiroshima atom bombs could have caused a loss of life potentially going into the millions (Figure 7). A large event of Chicxulub magnitude might occur every 100 Ma, but this statistical approach does not predict when it might happen next. Depending on the actual velocity of the Chicxulub impactor, that projectile might have measured between 5 and 15 km in diameter, although scaling from the amount of extraterrestrial material around the world indicates a value of about 10 km. However, current predictions of impact consequences suggest that even a 1-km-sized bolide might be sufficient to cause potential harm to mankind through global environmental catastrophe.

Projectiles enough are out there – comets in the Kuiper-Edgeworth belt and in the Oort cloud, and near-Earth objects (those asteroids that approach the Sun closer than 1.3 AU) are not particularly rare in the asteroid belt, largely a result



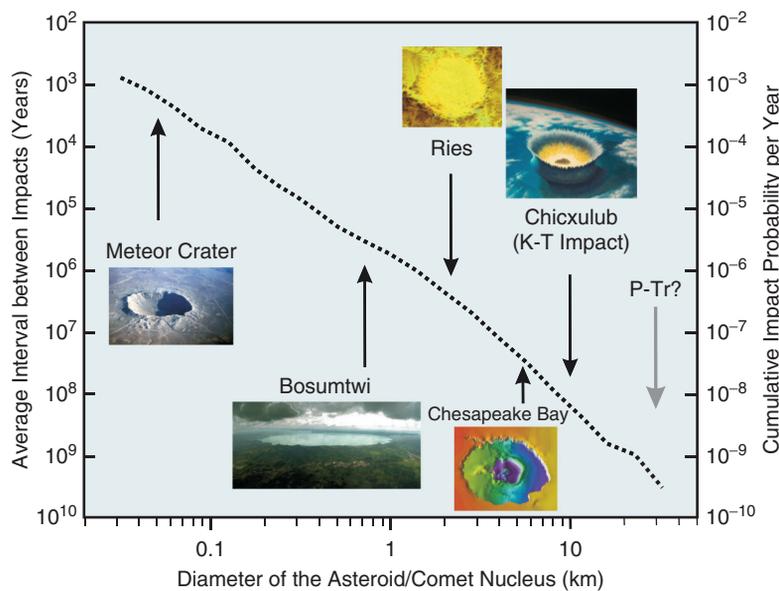
Asteroid Impact, Figure 6 Hubble space telescope image sequence of Comet Shoemaker-Levy 9 impacting Jupiter in 1994. Shown is a time-lapse sequence of the result of two fragments striking Jupiter. The fragments hit the atmosphere at about 60 km/s and left Earth-sized traces that could be observed for many weeks. Jupiter has a diameter that is about 12 times that of the Earth.

of the NASA-sponsored international Spaceguard surveying project. Data from these studies indicate that “the risk of any person’s death by impact prior to Spaceguard was estimated at about the same as dying in an airplane crash” – something like 1 in 30,000, but since the successful work of Spaceguard, this estimate has changed to 1 in 600,000 as the danger from likely still undetected asteroids.

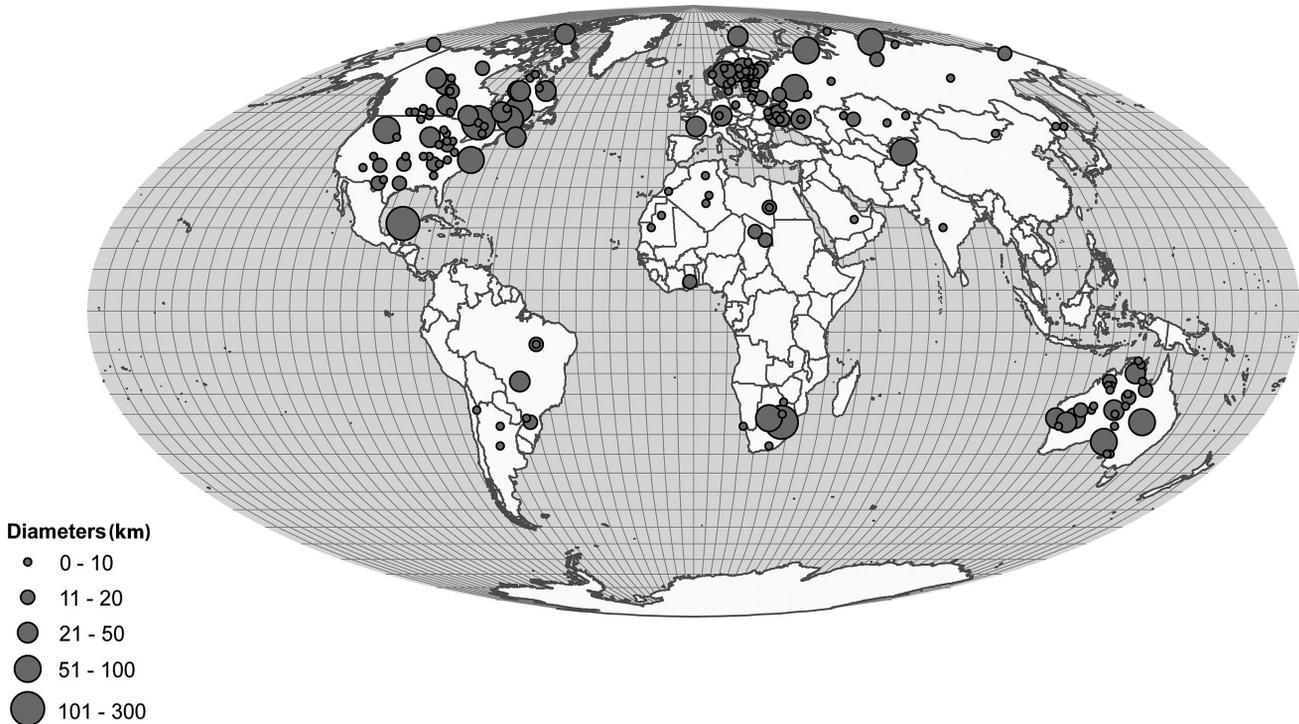
And still, much remains to be learned about the catastrophic impact effect. Space search programs for possible still unknown asteroids continue, and the danger from suddenly appearing comets remains anyway. The latter case provides a challenge for impact workers, as the behavior of large, low-density projectiles, and the effects of their impacts onto various planetary surfaces are far from being understood. The terrestrial impact record has to be improved to further constrain the past impact flux onto Earth, and the energy threshold for truly global devastation by impact still needs to be identified. Does it take an impact event of the magnitude of Chicxulub? Or was that impact particularly lethal because of the sulfate- and carbonate-rich target area at Yucatán? Can our highly evolved and, through its intricate civilization, highly vulnerable race survive a much smaller impact event, perhaps only creating a 40 km impact structure? And that will only take a 2–3-km-sized impactor. . .

Conclusions

Mineralogical, petrographic, and geochemical methods have been used for many decades in the study of the effects of asteroid impact in the formation of terrestrial meteorite impact craters. Currently about 180 impact structures are known on Earth (Figure 8). A clear hiatus in the history of impact-related studies was the realization



Asteroid Impact, Figure 7 Relation between impact probability and crater (as well as impactor) diameter (Updated from Montanari and Koeberl, 2000).



Asteroid Impact, Figure 8 Map of Earth with the currently known impact craters.

that K-T boundary bears unambiguous evidence for a large-scale catastrophic impact event (related to the formation of the 200-km-diameter Chicxulub impact structure, Mexico). Analyses of the K-T ejecta layers led to improved detection sensitivities for impact markers, allowing identification of smaller events and the study of their effects. Distal impact ejecta layers can be used to study a possible relationship between biotic changes and impact events, because it is possible to study such a relationship in the same outcrops, whereas correlation with radiometric ages of a distant impact structure is always associated with larger errors. Investigations of impact markers yield important information regarding the physical and chemical conditions of their formation, such as temperature, pressure, oxygen fugacity, and composition of the atmosphere. These data are necessary to understand the mechanisms of interaction of impact events with the environment and should ultimately lead to a better appreciation of the importance of impact events in the geological and biological evolution of the Earth. New geochemical techniques, such as the use of the Cr and Os isotopic systems, or analyses of comet-dust-derived ³He in sediments (e.g., Farley et al., 1998), have helped to confirm or better explain several important impact events. Recent improvements in analytical methods and techniques will certainly continue to influence our understanding of the interaction between cosmic bodies and the Earth.

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Cross-references

Asteroid
 Asteroid Impact Mitigation
 Asteroid Impact Predictions
 Comet
 Extinction
 Impact Airblast
 Impact Ejecta
 Impact Fireball
 Impact Firestorms
 Impact Tsunami
 Impact Winter
 Meteorite
 Torino Scale

ASTEROID IMPACT MITIGATION

Clark R. Chapman
 Southwest Research Institute, Boulder, CO, USA

Synonyms

NEA preparation; NEA response

Definition

The deflection of Near-Earth Asteroids and/or avoidance of the consequences of an impact.

Discussion

Near-Earth Asteroids (NEAs) present a potential hazard. Meteorites falling from the sky are a minimal threat. An NEA larger than ~20 m diameter could explode close enough to the Earth's surface to cause local damage whereas one larger than ~150 m could reach the ground or ocean with most of its cosmic velocity, causing an explosion far larger than any nuclear weapon tested. An NEA larger than ~2 km diameter could damage the global ecosphere sufficiently to threaten civilization.

Rescue and recovery would resemble that following most other natural disasters, should an impact not be forecast in advance. With warning, there are two basic approaches to NEA impact mitigation: (1) deflecting the NEA well before predicted impact by one of several technological approaches using spacecraft, and/or (2) evacuating regions around ground zero and preparing in advance for more widespread consequences, should there be inadequate warning to deflect the body or if deflection attempts fail.

Telescopic searches, and thus long-term warnings, are directed toward larger NEAs, that is, those larger than 100 m in diameter, and especially those larger than 1 km. If one is discovered with a decade or more advance notice, a space mission could probably be deployed in sufficient time to deflect it, and thus ensure that the impact does not happen. The best approach would be to launch one or more massive (e.g., 1 t or greater) spacecrafts, as early as possible before the expected impact, with an aim to collide with the NEA, triggering a small velocity change in the optimal direction such that it eventually arrives either early or late to the point in space where it would otherwise strike the Earth. Such “kinetic impactors” might be insufficient to deflect an NEA larger than ~1 km, in which case it might be necessary to detonate a nuclear device near the NEA in order to deflect it.

An NEA's response to a kinetic impactor or nuclear explosion cannot be perfectly predicted. Thus, it is possible that the NEA could be deflected into a so-called keyhole, resulting in it returning to impact Earth in a subsequent year. For this reason, it is highly desirable to have an observer spacecraft in the vicinity of the NEA to characterize its properties in advance of deflection and, afterward, to determine precisely how much deflection was achieved. If the observer spacecraft is equipped with thrusters so as to act as a “gravity tractor”, the mutual gravity between the spacecraft and the NEA could be used to precisely change the NEA's velocity sufficiently so as to preclude any further danger.

NEAs smaller than ~100 m diameter are much more likely to impact Earth than larger NEAs, but telescopes are less likely to detect them years or decades prior to impact. There is a good chance (perhaps as high as 50%) that one would be found during the last days or weeks before impact. Such short notice precludes deflection by spacecraft (exploding an NEA on its way in is an especially bad idea), but there would likely be opportunity for warning, evacuation, and other approaches to mitigating the expected damage.

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