Chapter 11

Asteroid impacts: Living at Ground Zero

Yon light is not daylight, I know it,

It is some meteor that the sun exhales,

Romeo and Juliet, Act III. Scene V.

William Shakespeare (1564–1616)

The Oxford Shakespeare, 1914

Bruno made clear that the Earth is a planet. Galileo saw spots on the Moon. The Earth accreted from a nebula around the nascent Sun. The Sun will eventually fail. But Newton's clockwork universe seemed to put the planets in their proper place, far away from terrene affairs.

Hints of astronomical effects of the Earth existed from antiquity. Meteors streaked across the sky. Occasionally stones fell to the ground; one receives a place of honor in Mecca. Yet these phenomena are rare enough that there was a tendency to regard meteors as an atmospheric effect and the fall of stones as superstition. In the late 1700s, the French Academy denounced falling stones, but abandoned their position after a large shower of stones on a village with French (hence reliable) observers. The very names meteor and meteorite (the rock that reaches the ground) reflect the belief that they came from the air, akin to meteorology - the science of weather. Shakespeare's emanation of the Sun is closer to the truth in the sense that many meteors contain direct condensates of the solar nebula.

Developments in the late twentieth century unified biology, geology, and astronomy, shattering this sense of security. I was an active participant in some of this work and close enough to observe how science worked in practice with the rest. As often, the division of science into specialties proved to be wanting in the face of new developments. The worldview of geologists and paleontologists against catastrophic events was a millstone on the feet of astrobiology. So was the view of many astronomers that nearby objects are unimportant.

Asteroids: Vermin of the skies.

Astronomers from 1801 to 1807 discovered 4 large asteroids between Mars and Jupiter, a gap that seemed to be “missing” a planet. This only added to the sense of order. More discoveries followed. With the advent of photographic recording, many professional astronomers regarded asteroids as an unimportant nuisance. The modern telescope moves to keep the fixed stars in the same place as the Earth rotates. The parallax of stars over one night is tiny so the stars appear as points. The exposure takes hours if the astronomers are after faint objects. In that time, the asteroid moves relative to the fixed stars because it and the Earth are orbiting the Sun. This leaves an unwanted streak on the plate. Looking for more asteroids after thousands had already been found was at best a “stamp-collecting” activity for amateurs and minor scientists. This aloof attitude changed some with the discovery of the asteroid Apollo in 1932. It crosses the Earth’s orbit. A collision is possible!

Figure 1: Bedded rocks are evident on the far wall of Meteor Crater Arizona. The blast tilted the beds elevating the rim of the crater. Gullies are already eroding the crater and filling the floor of the crater with sediments. The wall is around 200 meter high. The projectile was mostly vaporized and scattered widely with the ejected material. Photo by the author.

A hole in the Arizona desert. I retreat in history to 1891.The chief geologist of the United States Geological Survey explored a large hole in the Arizona desert (Figure 1). It is over a kilometer wide and almost 200 meters deep. Its rim rises 50 meters above the sounding plain. Grove Karl Gilbert (1843-1918) was one of the few geologists enlightened enough to consider the impact of a large meteor. Most of his contemporaries did not want to invite the return of the recently exorcised demon Catastrophe to a seat at the head table. Gilbert saw that the crater did not resemble any of the known volcanic features in the region and the meteorite iron was strewn everywhere. Yet he concluded that a volcanic steam explosion produced the crater.

He failed because he expected to find a large meteorite still there. He did not comprehend the immense amount of energy in an object hitting the Earth at cosmic velocities, probably around 20 kilometers per second. Modern calculations indicate that the iron projectile was 50 meters across. Much of it vaporized on impact. It hit tens of thousands of years ago.

Figure 2: Leonid Kulik, a Russian scientist, photographed fallen trees around the Tunguska impact over a decade after it happened. The trees fell radially away from the explosion in the air.

Tunguska. June 30, 1908. Meteorologists worldwide noted a pulse on their barographs (air pressure gages). They used the arrival times to show that an immense explosion occurred in a remote part of Siberia. Observers along the Trans-Siberia railroad reported a blinding flash. Fine dust spread through the upper atmosphere. At the latitude of Scotland, it scattered enough sunlight that the nights did not get dark.

The impact area was remote, even by Siberian standards. Scientists did not arrive until 1927. They saw evidence of a tremendous blast with intense heat. Fallen trees radiated out from the center of the blast with the upside scorched. At the center burnt trees still stood, stripped of their branches. The explosion occurred several kilometers, above the surface.

Modern research shows that the energy at Tunguska is similar to that at Meteor Crater, about that in a 15-megaton bomb. The strong iron object in Arizona penetrated the atmosphere intact, hitting with most of its cosmic velocity. The rocky Tunguska object came apart, like the *Columbia* space shuttle, from the great stress generated as it moved through the air. It flattened like a pancake, increasing its surface area until it converted its cosmic (kinetic) energy to heat and air pressure. The heat charred the ground and the local region of extreme air pressure ahead of the object produced the explosion. Chemical work on the dust (collected from Greenland ice) indicates that the projectile was a piece of the asteroid Vesta, one of the 4 asteroids discovered in the early 1800s.

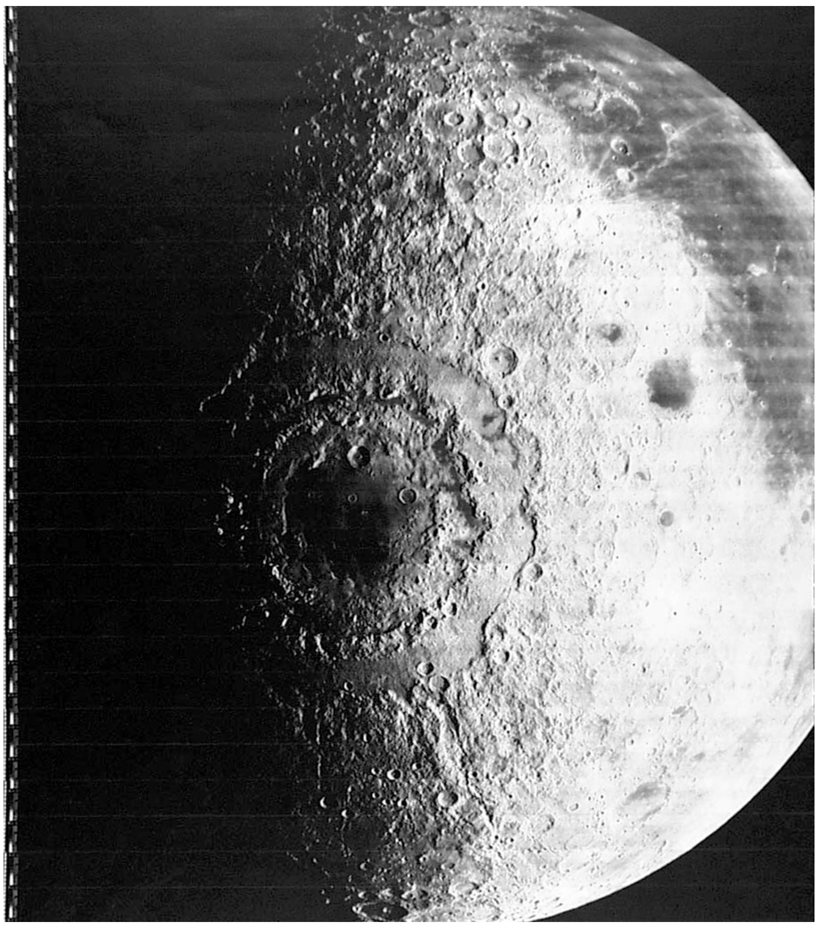


Figure 3: The Orientale basin records the last large impact on the Moon. Hence it is the best-preserved basin. The inner ring of the crater is 327 km in diameter. It was produced by a 70-kilometer diameter projectile about 3.8 billion years ago. The impact of this object of the Earth would have produced a pressure-cooker like atmosphere for 25 years. This would have been lethal to land biota and to shallow-water organisms, but only a nuisance to deep-sea organisms. Numerous younger craters cut the basin. They persist because there are almost no tectonics, erosion, or deposition on the Moon. The one exception is the basalt floor where lava flows filled the inner ring of the crater.
http://www.lpi.usra.edu/research/lunar_orbiter/bin/info.shtml?557

Lunar craters. Craters, Galileo's moon spots, cover the Moon (Figure 3). In the middle 1900s, speculation on their origin was taboo for geologists. The Moon was far away and they could not map it in the field. Impacts were recourse to catastrophism and maybe even to astrology. Uniformitarianism was a tenet of geology. It was taught to me as one in 1963. Even local catastrophes (like great local floods from the collapse of ice dams at the ends of glacial lakes) faced blind opposition before World War II. The overwhelming evidence for such events opened the first cracks in the facade of uniformitarianism.

The end of World War II brought an appreciation for the effects of large explosions and widespread use of air photos. The latter were a boon to field geologists. They could tell a lot before they left the office even though they needed to get ground truth. The Moon was not that much different than mapping from the office. It is easy even from Earth images to tell which crater cuts which. That is, one can use Steno's "laws" to get a relative geological time scale for the Moon, even though there are ambiguities. By the time of the Moon landing in 1969, geologists had made preliminary maps of the lunar surface.

Projectile science, helpful in wartime, contributed to the understanding of impacts. Impacts occur at velocities above the speed of seismic waves in rocks and also above the speed of antitank weapons. Impact generates a shock wave in a solid like a sonic boom around a jet in the air. The shock wave is intense enough to partly (or totally) melt rocks. It also vaporizes part of the projectile and the target. (Again the military origins of this science should be evident.) Shock produces minerals that form only at extremely high pressure, like dense forms of SiO_2 (from the quartz grains that make up the sandstone at Meteor Crater). The shock wave produces cone-shaped fractures with the point of the cone pointing back to ground zero. All this was there on display at terrestrial meteor craters for any geologists who cared to look.

Still many geologists were adamant that volcanoes not impacts caused the craters on the Moon. Much of the planning of the earlier Apollo landings had this in mind. The effects of impacts and shock were evident in the first samples. Most of the craters are over 3.5 billion years old. We see many craters on the Moon because it has been geologically inactive since soon after its formation. We see few craters of the Earth because erosion, sediment deposition, and tectonics rapidly renew the surface. For example, Ohare Airport in Chicago lies above an 8-kilometer-wide beveled and sediment-covered crater. Passengers see no hints of it.

Target Earth

As a beginning graduate student at MIT, I was of course not privy to the pre-Apollo discussions. The impact origin of craters seemed obvious to me and the initial results were no surprise. That is, there are many Earth-crossing asteroids and comets that are not being steered. Collisions were only a matter of time. I had only casual interest. The senior faculty were away studying the Moon. I was trying to study the tectonically active Earth.

The formal organization of lunar science was a major barrier to young scientists. Graduate students could publish their work on the Moon only as a co-author with the Apollo geophysics team members. I had no independent wealth and no interest in being unemployable. I did not start a thesis that I could not publish with my own name.

NASA continued to organize its lunar science around the Apollo teams. For example, one needed the invitation of a team member to attend the Lunar Science Conference. In the middle 1970s, this private club had become unworkable and was bad PR in an era of reduced funding for science. NASA scientists, like Tom McGetchin (1936-1979) and Roger Phillips, realized the need to bring new people into the planetary program. Their view held but the old practice did not immediately disappear. For example, I was on a NASA panel to evaluate grant applications in the early 1980s. A panel member raised an objection that a scientist was not part of the Apollo team. The grant applicant was 17 at the time of the first landing so that fact was not a big shock.

By then the existence of impact craters was a given. My initial interests were to understand the somewhat active tectonics on Mars and to compare it with tectonics on the Earth. For me, impacts provided a means of dating the age of tectonic events. (An old road sign typically has more bullet holes from bored hunters than a new one.) They also provided a means of getting at the depth of erosion within geologically inactive regions on the Earth where some craters remain. This is akin to seeing how much polishing is required to remove scratches from the hood of your car. In the late 1970s, I was visiting the Canadian Geological Survey in Ottawa with this in mind. While we were talking, a mining geologist phoned the survey scientist. At the end of the conversation, the scientist said with relief that this was the first mining geologist willing to rationally discuss understanding of impact craters as useful tool to find the depth of erosion and hence of exhumation of potential mineral deposits (rather than ignorantly berate the concept of craters). Blind uniformitarianism was crumbing, but not yet gone.

An Italian outcrop and an asteroid impact. In 1977, the problem of mass extinctions remained. The issue was much like that at the time of Darwin except that there were a lot more data. The Cretaceous-Paleogene boundary is the youngest (65 million years ago) mass extinction, if we do not count the recent demise of numerous animals at the end of the Ice Age and our continuing effects on the environment. High-press-value organisms like dinosaurs became extinct at the time of the boundary. The fossil biota changes abruptly at the time of the boundary. Intriguingly, the biota seemed impoverished above the boundary. That is, there are a lot fewer species just after than before and lots of empty niches.

A young geologist had recently taken a faculty position at Berkeley. Walter Alvarez (b. 1940) was a gradualist, but he wanted to see for himself. He was familiar with an outcrop near Gubbio, Italy. A centimeter clay layer exists between white Cretaceous and red Tertiary limestone. Alvarez thought that the clay might represent a long period of time where no carbonate was deposited. If so, the abrupt extinction would be an illusion.

He expected that the clay came from windblown sources on the land and that it fell at a constant rate in an offshore environment (like the nineteenth century methods discussed in Chapter 5). He knew the fraction of clay in the limestones so it was easy for him to calculate the relative times as the thickness of limestone that would yield a centimeter of clay. This was well and good, but he had a way to check his hypothesis. Meteorites continually fall on the Earth and much of the material, as from Tunguska or from meteors that burn up in the sky, comes down as dust. He expected this process to occur at a constant rate, as he knew it does from modern rocks. He expected the ratio of the trace amount of meteoritic material to wind blown clay to be constant in the clay layer and the limestones.

Alvarez had a high-tech way of detecting meteoritic material. Most meteors contain the rare element iridium in about its concentration in the early solar system. At the time of its formation, the Earth's iridium went into its iron core. Iridium is very soluble in molten iron. (Vesta's iron also went into its core taking its iridium with it. The lack of iridium flags the Tunguska object as coming from Vesta.) Asteroid impacts have added some iridium to the Earth since the core formed but the concentration of iridium in terrestrial rocks is far below that in meteorites. Luis Alvarez (1911-1988), Walter's father, had the equipment to measure the very minute concentrations of iridium that occur in natural samples.

The iridium results were startling. There was far more iridium in the clay than can come from any terrestrial source. Much of the clay is meteorite material. The clay is widespread. Extrapolating its thickness globally, a 10- to 20-kilometer diameter asteroid hit at the time of the extinction. It made a 200-kilometer diameter crater. A nearby supernova could not have produced the iridium spike.

Figure 4: Brush on the rim of Meteor Crater, Arizona illustrates that life has recolonized the area zapped by the impact. Individual organisms died but the impact was no threat even to local species. The bush in the foreground is about 2 meters across. Note the tilt of originally flat beds. Photo by the author.

This was not a coincidence. Could the impact have caused the extinction? To this time, geologists tended to regard craters as local curiosities. The meteor from Meteor Crater in Arizona killed snakes, lizards, and brush out several kilometers from ground zero, but the survivors from the surrounding desert quickly re-colonized (Figure 4). A 200-km diameter crater clearly zapped organisms unlucky enough to be at ground zero. The ejecta pile thrown out of the crater entombed organisms out for another 100 kilometers or so. But what was the global killing mechanism?

Attention focused on the clay later. The impact ejected this material briefly into space, then it came down mostly in dust-sized particles. Meteorologists are familiar with the effects of dust thrown above the troposphere by volcanic eruptions. It stays up for years and shades the Sun causing the climate to cool. The eruption of Tombora in 1815 in Indonesia caused worldwide crop failure, the year with no summer. The amount of dust from the impact at the end of the Cretaceous was enough to blot out the Sun. Photosynthesis stopped and the surface froze.

The Reagan administration made some effort to suppress this idea because of the analogy to winter following a nuclear war. They stopped NASA scientists from talking at meetings, but the idea was already out. Both Soviet and American scientists soon realized that an all out nuclear war was unwinnable. This helped end the cold war.

Further work showed other signs of impact. The worldwide iridium-rich layer contains shocked quartz grains, a good indication of impact. It contains soot from forest fires. This issue illustrates that scientists profit from recognizing that they lack expertise in other fields. The debate was thrashed out in my office at Stanford. I contended that darkness killed the forests and that they subsequently caught fire, especially a few years later when there were no dinosaurs left to eat the underbrush. This was the wrong track and the others in the room sensed it. Jay Melosh realized that the ejecta from the impact came down in over an hour or so at any one point. The projectiles came down with enough energy for the grains to glow like meteors. This was an easy calculation using Newton's laws for the material launched by the impact, conversation of energy, and the mass per area of the dust. The light from the glowing "meteors" was enough to start fires at the surface globally. Melosh realized that the problem is similar to radiant heat causing a forest fire to jump a firebreak. He contacted a forestry scientist and confirmed his intuition.

You can easily sense the intensity of the light yourself. It is about that in an oven boiler. Your hand and even paper do not instantly burn from the heat. Organisms had some time to shelter in burrows and under water. Water organisms could briefly come up to breath. Everything else like food forgotten for an hour in a kitchen boiler was scorched.

Crater hunt. Alvarez had no good idea where the crater was. It did not bother him much. In the last 65 million years, half of the Earth's surface has been subducted into the mantle. See Chapter 8 on plate tectonics. There would be no hope of finding the impact site in that case. Still geologists had half of the Earth to search and anyone familiar with a crater that might be the right age got busy. This had the desirable effect of dating a lot of impact craters, many of which are too small to have caused the clay layer. It had the bad feature of biasing the impact record of the Earth by making it look like there were an exceptional number of impacts around that time.

However, this intuitive qualm of sampling bias may be misleading. Recent work by astronomers using Newton's laws to backtrack the orbits of asteroids (see Chapter 3) indicates that the collision of two moderately large asteroids about 100 million years ago produced numerous fragments. Many of the fragments of various sizes eventually hit the Earth including the one 65 million years ago. Geochemists have recovered tiny pieces of this object and can compare their analyses with remotely sensed compositions of the surfaces of the surviving objects.

The impact turned out to be in the Yucatan of Mexico. A 180-kilometer diameter crater exists in the subsurface buried and preserved by sediments (Figure 5). It contains major oil fields developed before the feature was understood. The ejecta blanket with house-sized blocks exists nearby. At the time of the impact, the region was shallow water near the open Gulf of Mexico. A tsunami (seismic sea wave, called a tidal wave in the press before the recent event near Sumatra) went across the Gulf into Texas, tearing up the seafloor. The Atlantic coast east of Florida was in the lee of that landmass. Marine scientists have recovered the sand-sized ejecta and asteroid fragments layer from that region. As expected, the ejecta blanket is thicker and has larger pieces near ground zero.

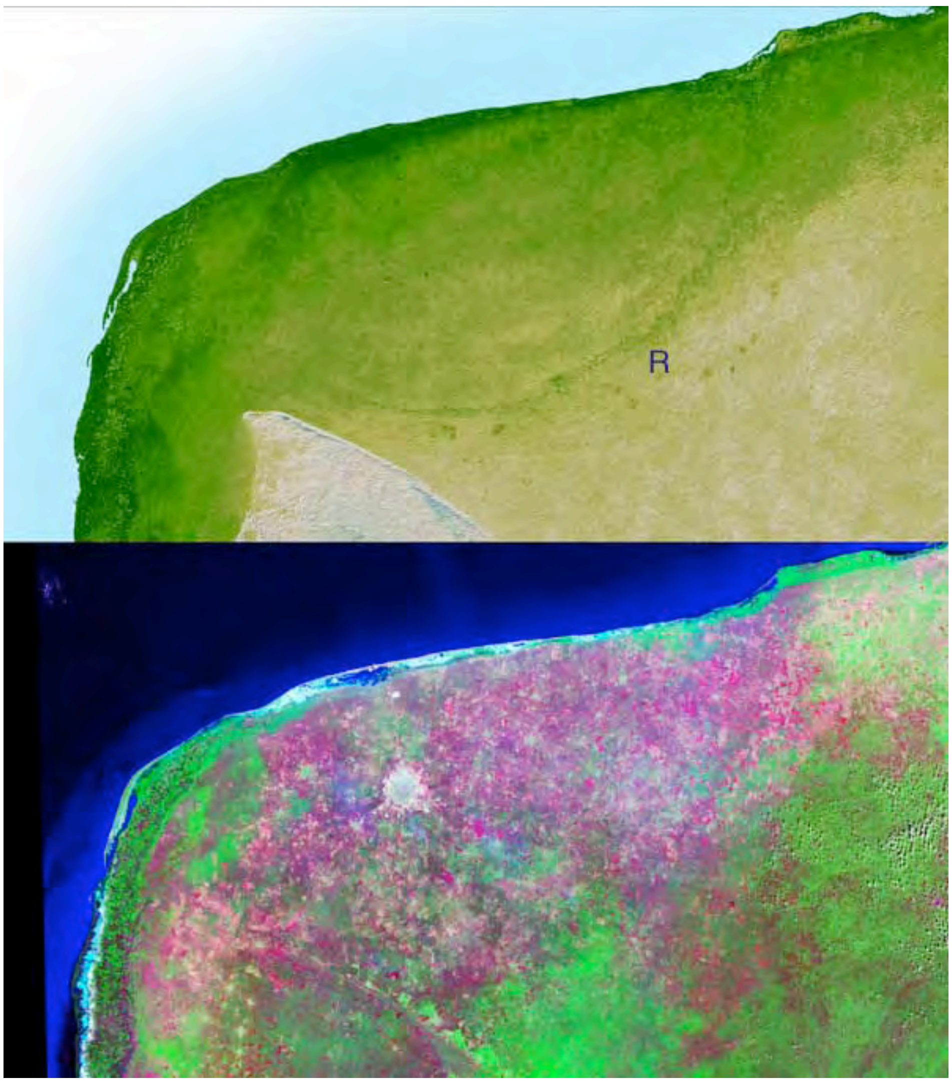


Figure 5: Radar (above) and false-color Landsat images of the Yucatan crater. The rim of the crater "R" (my annotation) is evident on the upper image. The actual crater lies beneath thick sediments but ground water flow has produced escarpments and sinkholes near the rim. The diameter of the circle is about 180 kilometers. http://www.jpl.nasa.gov/earth/features/chicxulub.cfm

Extinction. Many paleontologists abhorred the impact hypothesis. It went against their classical training against catastrophe. Most had little training in physics that prepared them for the effects of asteroid impacts. Some, like Alvarez, obtained the necessary expertise themselves and sought collaboration with other planetary scientists.

Some of the arguments against impact extinction were sophistry based on misunderstanding of the Linnaean classification. For example, a taxonomist arriving before the day of the impact would have classified birds as a type of dinosaur that got off the ground, like we consider bats a kind of mammal that takes flight. After the impact, non-avian dinosaurs were extinct but a species of bird survived and evolved into its species group. Dinosaurs go extinct only in the traditional classification. It is still a mass extinction whether one or a few species of birds survived and even if a non-avian dinosaur species can be shown to have survived. A second red herring is that some groups of species were already in decline at the time of the impact. This is unavoidable. Some groups of species are always in decline.

Figure 6: Microfossils similar to those used to date the Cretaceous-Paleogene impact. They are one-celled organisms called foraminifera. They lived on the seafloor near Pebble Beach California. The specimens are about a millimeter across. A knowledgeable paleontologist can tell from these fossils that the rocks containing them are around 16 million years old. Samples supplied by Jim Ingle. Photo by Pieter Vermeesch.

A more telling issue changed the way that paleontologists compile and present their data. Traditional paleontologists compile a species that lived anytime in the Danian (the first interval of the Paleogene named after Denmark where there are nice outcrops) in the Danian list. A species that lived in the Maastrichtian (the last interval of the Cretaceous after a locality in the Netherlands) is in the Maastrichtian list. This preordains that all the extinctions appear at the boundary between the two lists. The problem exists even with drill core. When a paleontologist grinds up a (say 10-cm length) drill core to extract fossils, all that can be said is that the fossil organism lived some time in that interval. Such bins make it appear that simultaneous extinctions occurred at every boundary between cores.

The sampling problem persists even when a paleontologist carefully records the actual position of each specimen, such as *T. rex*, for example. Paleontologists have a few tens of *T. rex* specimens over several million years. The chance of finding one killed by the impact is almost nil. Even more common specimens, for example ones that occur once in each meter of section, cause problems. If all these organisms went extinct exactly at the boundary, the last specimen of each will range from a few centimeters to a few meters below the boundary. It will appear that the different organisms went extinct gradually over the interval represented by a few meters of section. That is, the recorded extinctions seem to anticipate the impact. Walter Alvarez used microfossils of one-celled photosynthetic organisms (Figure 6). They occur in vast numbers so he had no sampling problem.

Figure 7: The southwestern desert would be a very dangerous place after an impact. Intense fire would consume exposed vegetation, roots, and buried seeds. Any animals surviving in burrows would emerge into freezing conditions with nothing to eat. Plant species became extinct after the Cretaceous-Paleogene Impact in this region. Photo by the author.

What are the predictive implications of the impact hypothesis? The killing mechanisms are heat followed by darkness and cold. The heat was particularly intense near the impact over western North America (Figure 7). The fireball melted the exposed surface in addition to vaporizing any exposed vegetation. Seed plant species went extinct. Ordinary forest fires do not kill all the seeds in the ground. [see Do it Yourself Seedbank] A few individual plants survived in favored areas like deep swamps (Figure 8). The vegetation after the impact is ferns that disperse rapidly as spores in the wind. It took some time for seed plants to disperse and catch up.

Figure 8: Swamps like the Everglades provided a safe place for many organisms during the Cretaceous Paleogene impact. Intense heat immediately after the impact burned vegetation to the water line. The water maintained clement temperatures below the surface. In the subsequent cold, the water did not freeze all the way to the bottom. Plants survived as roots and seeds at the bottom. Swamp ecology depends on rotting vegetation, not this year's photosynthesis. The food chain based on rot survived the dark. The ancestor of the Florida alligators and crocodiles survived at the top of such a food chain. It was one of the largest organisms to survive. Photo by the author.

A modern example of slow dispersal is the American chestnut. It has a large seed that is planted by squirrels. When Europeans arrived in the formerly glacier-covered area of Michigan, it was native only on the eastern side of the state. Oaks whose lighter acorns get carried a bit farther by squirrels were dispersed across the state.

Biota dependent on this year's photosynthesis did poorly, including plankton in the open ocean, which are vulnerable to darkness but not heat. The darkness was bad because the target rocks contain calcium sulfate $CaSO_4$ beds. (For nonchemists, calcium sulfate is the ingredient of drywall and plaster.). The vaporized sulfate, like sulfate from volcanism, stayed in the air much longer (like 10 years) than rock dust (a year). The impact occurred in early June (we know this from what flowers got killed by the clay layer). This is a particularly bad time in the Northern Hemisphere as everything is overextended in the expectation of plenty. Animals not dependent on this year's photosynthesis survived. This includes pond biota dependent on rotting vegetation (Figure 8), like crocodiles, and our insect-eating ancestors in rotting tree roots. This gives us the survivor's illusion of good luck.

Permian-Triassic extinction: The Great Dying

Early paleontologists placed the Mesozoic-Cenozoic era boundary at the marked break between Cretaceous and Paleogene fossil species. They placed the Paleozoic-Mesozoic era boundary at the break between Permian and Triassic fossil assemblages, Numerous species groups vanished at the end of the Permian Period as with the end of the Cretaceous period. The biota following the extinction are highly impoverished. Careful work indicates that there where really two extinction events. This first occurred 260 million years ago, 8 million years before the end of the Permian.

Another crater hunt. Scientists productively spot the analogous situations. The search for an end-Permian crater and its iridium-rich ejecta layer was underway soon after the recognition of the Cretaceous-ending impact. There have been claims that the crater has been found. However, the sites are currently quite inaccessible, under Antarctic ice and beneath the seafloor near Australia. The ages of these features and whether they are really impact related are still uncertain.

There is at best tantalizing evidence of an impact horizon. Poor rock preservation is the culprit. The Permian Period ended at a time of low sea level. Erosion rather than deposition dominated over the continental platforms. Almost all the Permian seafloor has since been subducted. Only a pittance of deformed of deep marine Permian sections persists on land.

Grabbing at straws from space. The dearth of hard evidence has sired much speculation about other extinction mechanisms. This speculation is useful if it leads to the testable prediction of expected survivor and casualty manifests.

At one end, iridium need not be associated with an impact layer. Astronomers have found asteroids that are chunks expelled from the large asteroid Vesta by a large impact. A projectile from Vesta (or a similar non-surviving large asteroid) would contain no iridium. Comets are poor in iridium relative to most asteroids, but still rich in iridium compared with Earth rock. Fragments from large icy objects from outside the orbit of Neptune provide another source of iridium-free projectiles. These objects, including Pluto, probably melted into water-ice shells with rocks and iron going to their centers early in the history of the solar system. Shocked mineral grains in sediments would still aid in recognizing impact ejecta from iridium-poor projectiles.

Gamma ray bursts and supernova have come up. Nearby events are likely over geological time. The likely killing mechanism is destruction of the ozone layer by gamma rays allowing ultraviolet light to reach the surface. Bad times would have lasted a few years. It is hard to see how UV light would kill seeds in the ground and plant roots. Marine plankton deep in the photic zone would be spared. So would animals in ecosystems that did not depend on this year's photosynthesis. The modern ozone holes over the Antarctic and the Artic provide some analogy. (The release of industrial chlorocarbons caused the problem. They are now banned.) There has been no mass extinction or even big die-off of photosynthetic plankton from the ultraviolet light. Neither was the Permian extinction notably bad on land plants.

Unstable evolution and climate? Staying at home, climate and ecology may have become unstable. However, the obvious suspects seem to be too slow to have produced a sudden extinction event.

Starting with the profoundly sluggish, the continents gradually assembled into a single landmass Pangea by the late part of the Permian. Biota on previously isolated continents exchanged. Like biota on oceanic islands with the arrival of rats, many species were found wanting in their new circumstances. Extinctions did occur, including the Glossopteris flora that Wegener used to show that the southern continents were once joined. However, these extinctions did not leave an impoverished biota in their wake. For example, seed ferns replaced glossopteris species.

Second, the interior of Permian continents was mostly dry land. The great shallow inland seas of the earlier Paleozoic were a distant memory along with their environment. Intense ice ages sequestered water in ice sheets, exposing continental shelves. Overall, living space for shallow marine organisms dwindled along with their preserved record. Ocean basins vanished all together in continental collisions leaving high mountain ranges, including the Appalachians. Massive lava flows vented in Siberia; the largest were thousands of cubic kilometers over ten-year periods. I return to the lava but I first discuss the effects of sealevel change.

These events clearly locally stressed biology. The Black Sea provides a recent analogy. Sea level during the last ice age dropped below the level of the Bosporus, cutting it off from the Mediterranean Sea. The rivers entering the Black Sea did not have sufficient volume to match evaporation. The Sea dried up leaving some saline swamps and a fertile plain. Marine organisms trapped in the Black Sea died, but their relatives in the Mediterranean Sea merely lost potential living space. The Black Sea filled with rising sea level about 8400 years ago. The flood drowned and displaced biota, including late stone-age farmers.

Earth scientists thus seek an unstable event triggered by sea level change and/or the concentration of land into one super-continent. Again the Black Sea provides an analogy. Its deep waters are anoxic and rich in hydrogen sulfide H_2S. Rapid overturn of the ocean would release this toxic gas into the air. Reaction of H_2S with atmosphere oxygen O_2 would produce sulfuric acid H_2SO_4. This added to the sulfur degassed from Siberian lavas.

Methane is another suspect gas. Today, it accumulates as a solid compound with water, called cathrate. Cathrate is stable at moderate depths on the seafloor and at temperature below several degrees Celsius. It accumulated in shallow sediments above where methane forms from organic matter in deep sediments. Rapidly dropping sealevel may have caused cathrate deposits on the seafloor to become unstable. Methane is a potent greenhouse gas. In enough quantity like hydrogen sulfide, it would be a sink for oxygen in the air. However, oxygen is a major component of the air, 21% at present. It is highly unlikely that vented gases consumed enough oxygen to drop the oxygen concentration in the Permian air below the level required by animals.

Illusion of sudden extinction? These hypotheses for climatic disasters, however, fail the test of quantification. There is simply not enough gas to cause global problems. This difficulty and the lack of a good rock record left open the possibility that the end Permian extinction is only apparent from a poor rock record, the very hypothesis that Walter Alvarez sought to test for the end-Cretaceous extinction. Again the Black Sea provides analogy. A geologist viewing deposits on exposed on land 252 million years in the future would see the abrupt demise of marine organisms when the sea dried up at the start of the last Ice Age. These future geologists viewing similar breaks (say from the Black Sea at the last start of the Ice Age and lakes that dried up in Nevada at the end of the Ice Age) in the global fossil record of today might incorrectly correlate them as being synchronous.

The late Permian and early Triassic record in fact indicates seriously poor sampling especially of hard-to-identify species, like small sea snails. Species groups appear to vanish by the end of the Permian and are absent in early Triassic rocks. Yet representatives of these groups, called Lazarus species, reappeared later. The groups never went extinct. Rather their species lived in places that have not been studied, have poor preservation, or have even been obliterated by tectonics and erosion. This might imply that a large number of other species could have survived the end of the Permian only to become extinct later without leaving a trace.

Further the first mass extinction 260 million years ago may be an illusion. Before this time shallow tropical seas teemed with life in west Texas. These reef deposits are very well exposed; paleontogists have collected and named vast numbers of species. At 260 million years ago, circulation in this sea became restricted and its water highly saline. It ceased to be habitable be normal marine organisms. It is likely that some of the Texas species became extinct. However, many of them may have persisted in nearby poorly sampled regions.

Lava, coal, acid oceans, and global warming. Geologists have recently obtained a viable hypothesis for the cause of the Permian extinction. They have not yet had time to explore its implications or to appraise if the global time of events is really synchronous. Concern about global climate change (see Chapter 14) and natural metallic iron, a rare geological curiosity, provided analogy as well as a dire warning.

I start with what may appear to be a digression. Demand for iron and steel for railroad tracks, trains, bridges, and ships drove (and carried) global commerce from the middle 1800s until the 1950s. Cars and trucks added to the demand after 1900. Iron and steel making are conceptually simple and known from antiquity. Metallurgists heat iron ore with coal. In terms of chemistry,

$2Fe_2O_3$ (iron (ferric) oxide in iron ore) + 3C (carbon in coal) ⇒ 4Fe (iron metal) + $3CO_2$ (carbon dioxide gas)

Modern industrial-scale iron and steel making is highly sophisticated as it is important to control the composition of the impurities in the metal and the rate that it cools.

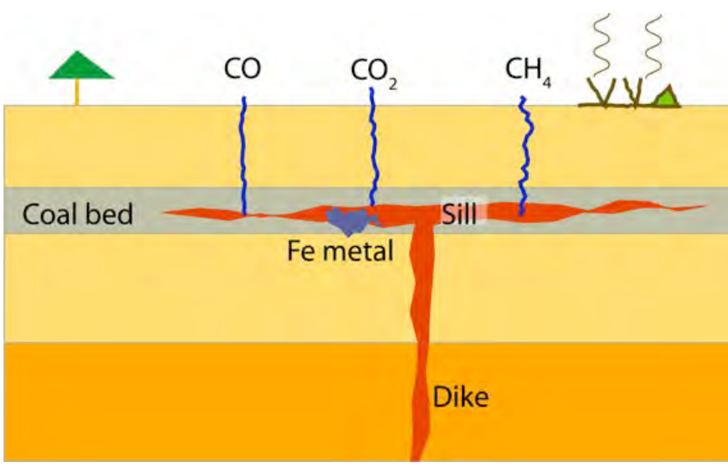
Metallic iron formed this way during geological time when molten lava intruded into coal beds. The black volcanic rock basalt it typically involved. It is rich in ferrous iron oxide FeO and quite common. The iron oxide in the rock reacts as in a blast furnace,

2FeO (iron (ferrous) oxide in basalt) + C (carbon in coal) ⇒ 4Fe (iron metal) + $3CO_2$ (carbon dioxide gas)

Iron metal formed in this manner occurs widely in Siberia. Stone age people alertly wrought the metal into tools. Until 2000, geologists tended to regard it as an unimportant local rarity, as they had done with impact craters 50 years earlier.

However, careful geological mapping in the last few years indicates that the amount that basalt intruded vast deposits of coal. These underground events occurred at the same time that millions of cubic kilometers of basalt flowed out onto the Siberia surface.

Mechanically, coal is easily deformed compared with other sediment beds. Lava ascending from deep in the Earth encountered 10s of meter thick coal beds beneath Siberia. It was easier for the lava to move sideways along a coal bed than to continue upward to the surface. The final result was vast horizontal sheets of basalt within coal beds, that is sills (See Chapter 5). Individual intrusions of basalt heated thousands of cubic kilometers of coal in weeks to years. This is much more coal that humans have mined over history.



The blast furnace reaction released CO_2 to the air. In addition, the Siberian coals where "soft" when the basalt intruded. They contained water, methane, and volatile hydrocarbons. The heat of the intrusions drove off the methane and hydrocarbons into the air. The water reacted with the carbon in the coal

$$3C \text{ (coal)} + 2H_2O \Rightarrow 2CO \text{ (carbon monoxide gas)} + CH_4 \text{ (methane gas)}$$

This reaction goes quickly at high temperatures. It is the basis of an industrial process to produce cooking gas where natural gas is unavailable. These gases along with CO_2 are lethal hazards for coal miners who call CO_2 blackdamp, CO whitedamp, and CH_4 firedamp.

Hot coal is fluid with properties similar to lava. The volatiles in hot coal act much like the volatiles in lava, causing explosive erupts. Most erupted the coal and basalt mixture ignited sending more CO_2 into the air. Fly ash and mercury from the erupted coal fires have been found in Canada. It is still unclear whether the bulk of the end-Permian CO_2 came from coal or from organic-rich (black) shale underlying the coal.

Methane and CO_2 are toxic only when they displace air with oxygen. This calamity may have occurred locally in Siberia, but the volume of gas was far too small for it to occur globally. These emanations from hot coal are, however, powerful greenhouse gases. Global warming began as soon as the soot from the burning coal settled. Temperature sharply increased over a period of a few years. Unlike the current global warming, there was no time for organisms to adjust their ranges toward the poles. Polar organisms had nowhere to run.

Warmer temperatures were not the most serious problem for many marine organisms. Carbon dioxide dissolves in water to form an acid

CO_2 (carbon dioxide in water) + H_2O (water) $\Rightarrow$ H^+ (hydrogen ion in water) + HCO_3^- (bicarbonate ion in water)

The coal intruded by basalt released its CO_2 over a few years. This was not enough time for the shallow water in the ocean to mix with deeper water. The shallow water became acid globally. The effect was deadly. Acid dissolved the calcium carbonate as in the shells of marine organisms:

$CaCO_3$ (calcium carbonate in shell) + H^+ (hydrogen ion in water) $\Rightarrow$ Ca^{++} (calcium ion in water) + HCO_3^- (bicarbonate ion in water)

Acidic conditions kept shelly organisms including coral from making new shells. The acidic water mixed downward over a decade. Burnt coal, unlike basalt, is a voluminous source of sulfuric acid as with modern acid rain. Repeated episodes of coal burning and CO_2 release eventually made the deep ocean somewhat acid. Over 10s of thousands of years, the ocean reacted with basaltic rocks on the seafloor and ceased being acid, too late to save countless marine species.

Finally, carbon monoxide is toxic in trace quantities with prolonged exposure. You have been warned to be careful in closed garages. The question arises whether it could have led to the demise of species of land animals. Available evidence shows this poisoning is unlikely at the end of the Permian. Carbon monoxide has a short lifetime in the air. It might have mixed throughout the northern hemisphere where Siberia was at the end of the Permian, but not into the Southern Hemisphere. We would thus expect that it would kill northern species but not southern ones. Paleontologists do not observe this pattern.

Bigger ammo on the Early Earth

We now go back near the dawn of the Earth. I moved from a bit part to center stage in this phase of impact astrobiology. I served as the geological member on a Space Sciences Board committee in the middle 1980s. Our task was to advise NASA on issues related to astrobiology (not called that then) and planetary quarantine. Initially, my interest involved tectonics on the early Earth and Mars. Impacts on the early planets kept coming up. The projectiles that caused 1,000-kilometer-diameter basins on the Moon and Mars were much bigger than the pinprick Cretaceous-Paleogene impact.

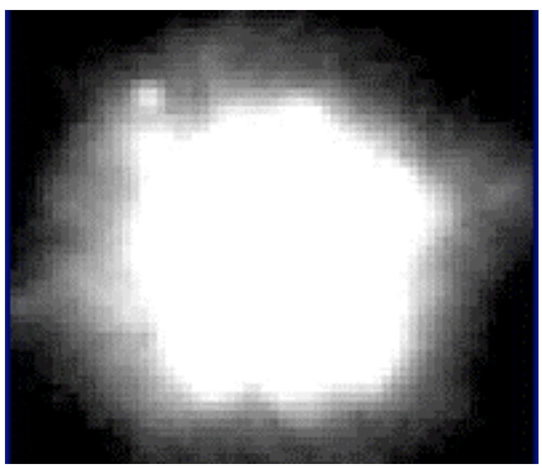


Figure 9: The asteroid Eugenia has the size 215-km of the largest projectiles known to hit the Moon and Mars. A small moon orbits it on the upper left. The asteroid is over-exposed (and the disk too wide by a factor of ~3) to bring the satellite into view. Application of Newton's laws allowed astronomers to determine the mass and density of Eugenia. It is only 1.2 times as dense as water and may consist of water ice, which is stable at this distance from the Sun. The space program had provided such meager information on medium and large asteroids by 200. There are now close up images of small asteroids, and of the large asteroids Vesta and Ceres. Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii.

Was there a global killing mechanism? The discussion in my office and my off-base analysis of forest fires pressed home the importance of heat. I was also familiar with the hypothesis that life originated at hydrothermal vents. Could I put the two together? Yes! If heat is the killing mechanism, high temperature organisms will be the last to die. This is thus the safest place for life to evolve. Thus life originated within the vents. Too simple to be wrong!

I sent a paper to the leading scientific journal *Nature* and promptly ran into the aversion of traditional paleontologists for physics. One reviewer even insisted that a well-known paleontologist had already concluded that no life could survive when asteroid impacts were frequent on the early planets so there was no point for geophysicists to look at the issue. The Hadean was defined as lifeless. Neither reviewer objected on the alternative ground that impacts were merely local effects.

Quantification is a good antidote for dogmatism and *Nature* welcomed our next effort. I vowed to be more thorough and began working with Kevin Zahnle, Hal Morowitz, and Jim Kasting at nearby Ames NASA. It took some time to work out the size of a body needed to boil the ocean, around 500 kilometers diameter. However, a 300-kilometer diameter object heats the ocean and leaves only thermophile survivors in the subsurface (we did not have that number then). We also examined the lunar and Martian records and concluded that only a few such bodies hit the Earth.

The vaporized rock from a projectile greater than about 30-kilometers diameter is too massive to immediately radiate its heat to space. Rather the rock vapor surrounds the Earth has a hot gas. It mixes with and overwhelms the pre-existing atmosphere. It radiates heat downward to the surface boiling the other and out to space.

Astronomers provide a useful analogy for the physics. The conditions at the top of rock vapor were similar to thus in the atmosphere of cool red stars. Silicate grains condense making the lower atmosphere opaque. In the case of the Earth, heat radiated from the top of the rock vapor cloud. Rock rain fell to the ground. It took less than a day for the rock to rain out from a 30-km diameter impact and months from an impact that boiled the ocean.

Figure 10: Rock-rain bed in 3.24 billion year old sediments from southern Africa. The droplets, about 1 mm in diameter, froze when they hit the sea surface. They contain iridium from the projectile, which was 30-60 kilometers in diameter. Sample from Don Lowe. Photo by the author.

Overall, heat as the killing mechanism makes things simple. We needed only apply conservation of energy. We needed to export the good lunar record to the Earth where no record of early impacts exists. We were concerned only with the biggest objects that could globally zap microbes. The largest object to hit the Moon had a 200-kilometer diameter. The Earth is larger and got hit more, like a deer in a wood full of drunken hunters gets hit more than a rabbit. With a little mathematics, about 16 objects larger than 200-km diameter hit the Earth.

To make the problem well posed, we considered what would be needed to wipe out various types of ecosystems on the Earth. This is a common assumption in astrobiology to which the second review of my first paper objected. At a minimum, we can say something is possible. A photosynthetic ecosystem (one being at the surface) is most at risk. A deep subsurface one dependent on rocks is safest. It turned out that we made a testable hypothesis.

Bottom line: A night to remember

The *Titanic* makes an exciting story because live witnesses survived to tell the tale. Although we did not appreciate it when we submitted to *Nature*, there are plenty of potential witnesses to the large impacts on the early Earth, the descendants of the microbes living at the time. They record the story in the genomes of all extant life.

Back to the *Titanic*, we can learn a lot about the social system from the survivor and casualty manifests. Wealthy women and children survived. Gentlemen and steerage passengers did not. There were exceptions. The event was too local to decimate either the gentry or the poor. For example, my father-in-law, then an impoverished Jewish child, survived because his slow train from Russia caused him to miss the boat.

The end-Cretaceous and end-Permian extinctions provide analogy to the early Earth. Natural selection does not directly adapt organisms to conditions that have not yet occurred. It does adapt organisms to the conditions that they did face. Adaptations driven by one selective pressure sometimes pre-adapt organisms for another. In the case of the Cretaceous, animals apt at sheltering underground or underwater and ecosystems not dependent on this year's photosynthesis did best. For the Permian, we would expect acid-tolerant and heat-tolerant organisms and ecosystems to survive.

Both events are partly evolution progressing in ways that made the global ecology vulnerable to unusual events. Coal is a direct deposit for carbon from photosynthetic plants. The sulfate beneath the Cretaceous target in the Yucatan was ultimately a product of oxygen from photosynthesis. In neither case did the extinction wipe out photosynthesis; not surprising, had this happened there would probably be no intelligent life around to comment.

Back to the early Earth, thermophile organisms would have been the final survivors of any large impact, particularly those living in the deep subsurface. The physics are again simple. The ocean boils and the heat can only radiate out at cloud top temperatures. Like now, it rained about a meter per year, but the rain lasted for a few thousand years. The heat pulse from the hot surface slowly propagated down into the ground by conduction. As already noted in Chapter 5, the depth of heat penetration scales with the square root of the time that the surface was hot. Rocks above about a kilometer depth were heated during the few thousand-year period when the ocean boiled and condensed. Deeper rocks did not heat up much, but were hot enough already that they housed only thermophile organisms (Figure 9). Do we see the expected survivors? Yes. The last common ancestors of Bacteria and Archaea are thermophile. The last common ancestor of all life (LUCA) is probably thermophile. We see plenty of hints that LUCA lived within rocks.

Figure 11: Outcrops from uplifted oceanic crust in California illustrate the goldilocks zone. The basaltic pillows in beds dipping to the left were buried about a kilometer below the surface (top). Hot but habitable water circulated through them forming the white veins. These rocks would have been a safe place for microbes in a large impact. The basaltic dike rocks were deeper and hotter. The olive green veins containing a mineral called epidote formed at around 400°C too hot all the time for life (bottom). Smartville area. Photos by the author.

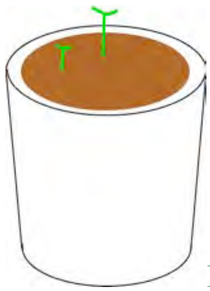
Does this mean that life originated in hot vents? No! We found that there were only a few very dangerous impacts on the Earth. They were 10s to 100s of million years apart. There was plenty of time for life to originate somewhere, colonize the Earth, and get decimated by a great impact. LUCA is a highly evolved organism, a nice candidate for a survivor, but not the first common ancestor.

Does this mean that all mass extinctions result from impacts? Again no. We have good evidence only for the Cretaceous-Paleogene extinction and as discussed above the environment may have become unstable at the end of the Permian. We cannot generalize a lot to extrasolar planets. We have begun to discover a earth-size terrestrial planets around other stars. We do not know if the asteroid flux on the Earth is heavy, average, or light for a typical planet.

Notes

Virtually all earth scientists have accepted the reality of the impact crater in the Yucatan. The connection of the impact to specific extinctions is controversial. One issue is that erosion exhumes fossils, which are then deposited in younger beds. Another is poor sampling of the record of large flashy species. A third is that the thick (100s of meter to kilometer) tsunami deposits near and above the crater formed in minutes to hours under catastrophic conditions that have not since returned to the Earth. Methods for examining slowly deposited sediments are inapplicable. There is still some tendency for geologists to assume that a kilometer of sediment took a long time to accumulate.

Exercises

 It is hard to get at the high energies of impacts, but you can see for yourself a refuge from normal forest fires and bad growing years. Swamps were a similar refuge for the Cretaceous-paleogene impact. There are a lot of ungerminated seeds in soil any one time. This seed bank serves as a backup if this year's crop gets wiped out. There is thus selective pressure for a few seeds staying in the ground more than one year.

Gather soil in flowerpot, preferably from a place that looks at least somewhat wild. Remove any growing plants. Note how wild your spot is.

Record location from the map and date. ___________________________

Water flowerpot to keep it somewhat wet. Watch and record dates when seeds come up. Record number, if more than one comes up in a day. It will help in counting if you pull them.