The end-Cretaceous mass extinction and the Chicxulub impact

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What Do We Know About Massive Meteor Impacts?

Meteors crash into Earth's atmosphere every day, but almost all crumble into dust before they reach the surface. Occasionally, a larger fragment, called a meteorite, makes it all the way to Earth's surface. There have been cases of people injured and property damaged by meteorites. One of the more spectacular recent atmospheric impacts occurred over Chelyabinsk, Russia, in 2013. The meteor exploded in the air, generating a shockwave that shattered windows all over the city, sending over a thousand people to the hospital. To make matters worse, the impact occurred in February, during very cold weather, and it was hard to heat those homes until the windows could be repaired. Russian scientists recovered several meteorite fragments months later; they had fallen harmlessly into a nearby lake. In 1908, the atmospheric explosion of a comet or meteor over Tunguska in Siberia flattened trees in such a large area that the devastation was still visible 21 years later when a scientific expedition came to investigate the blast. Historical records from China describe a meteor shower, during which stones the size of goose eggs fell out of the sky and killed thousands of people in AD 1490.

As terrible as these impacts were, none of them left craters. According to the Earth Impact Database (PASSC, 2015), there are almost 200 verified craters on Earth's surface from even bigger impacts, almost none of which occurred during recorded human history. Oddly, most of them were not identified as impact structures until the late 20th century. Geologists generally attribute features like craters and canyons to events we can see taking place today or in recorded history, like erosion by rivers, gradual movement of rocks on either side of a fault by earthquakes over time, volcanic eruptions, etc. Craters left behind by massive meteor impacts resemble those created by explosive volcanic eruptions, but with one critical difference: there's little or no igneous rock in impact craters (unless the crater was in igneous bedrock). When geologists were forced to come up with explanations to explain structures like Coon Butte (now called Barringer or Meteor Crater) in Arizona, USA (Fig. 1) and Ries Crater in Germany, they debated whether they had been created by meteor impacts or by cryptovolcanism, volcanic explosions that left little or no ash or igneous rock behind.

Figure 1: Satellite image of Barringer or Meteor Crater, Arizona U.S.A. The dark rectangle at the top is a museum. (http://earthobservatory.nasa.gov/IOTD/view.php?id=39769)

Over the 20th century, the scientific community gained a better understanding of impacts, but found no evidence for cryptovolcanism anywhere. Very few scientists accept cryptovolcanism now. Craters and impacts big enough to leave them have been observed on the moon and elsewhere in the solar system using technology like telescopes and spacecraft with cameras. Also during that time, geologists discovered minerals that could be used as reliable indicators of asteroid impact. Coesite and stishovite were created as artificial crystals in laboratory settings and later found in nature as minerals at Barringer Crater. They were also found at nuclear-weapon testing sites, along with shocked quartz. Shocked quartz has become very useful for scientists because the linear patterns that distinguish it from ordinary quartz are easy to recognize under a microscope (Fig 2). Another important feature of shocked quartz is that it forms under high pressure, but only under a range of temperatures similar to those found at Earth's surface, as opposed to the high-temperature conditions inside a volcano or a magma chamber.

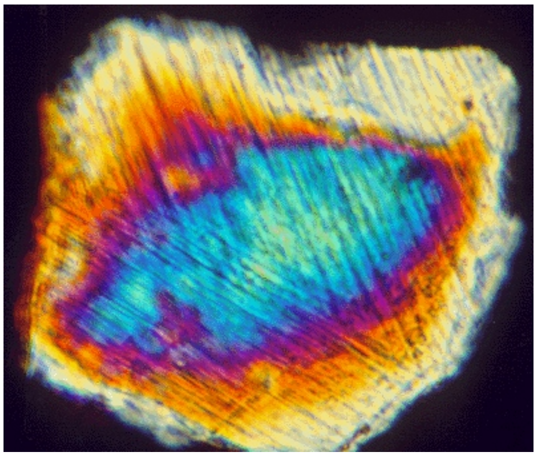

Figure 2:a shocked-quartz grain from the Chesapeake Bay Impact structure. Image from USGS-NASA.

Barringer Crater is a simple crater (Fig. 3a). Meteors big enough to leave a crater actually explode before or on impact. The crater is formed by the force of the explosion rather than by the impact itself. The heat from the meteor is intense enough to melt some of the surface rock. The blast shatters the rest. The pressure on the solid bedrock layers beneath is so intense that the bedrock becomes temporarily capable of stretching and bending, even though it is still solid. The crater forms as the bedrock is pushed away from the explosion. However, the rock quickly loses that flexibility, becoming rigid again, before it can regain its original shape. The resulting crater is much larger than the meteor that originally formed it.

More severe impacts leave behind complex craters (Fig. 3b). In this case, the bedrock in the middle of the crater remains flexible long enough to not only bounce back to its original elevation, but to keep going. The bedrock becomes rigid again before it can descend again, leaving behind a hill in the middle of the crater called the central uplift.

How Could a Massive Impact Cause a Mass Extinction?

The force of a massive impact alone will crush every multicellular organism in the crater. The blast wave it generates will kill organisms across an even greater distance, but it will have to trigger a series of other effects to cause a global pattern of extinction.

When a large meteor explodes at or near the surface of the Earth, pulverizing surface rock, the shockwave will scatter the dust from both the meteor and the impact site high into the atmosphere. The explosion may also generate enough heat to trigger forest fires or grass fires, which will produce ash that is also blown into the atmosphere. These solid particles can block or reflect sunlight. They can remain suspended in the air for months and will be spread around the hemisphere by high-altitude winds.

Historians observed similar effects from the eruption of a stratovolcano, Tambora, in the early 19th century, which ejected so much ash that the amount of sunlight reaching the Earth's surface was significantly reduced as it spread over Northern Hemisphere. The following year was called "The Year without a Summer" because the weather was so cold. Crops that survived the frost provided a meager yield because they could only photosynthesize slowly with weak sunlight.

A multi-year "impact winter" caused by a massive impact could be even colder and darker, blocking so much light that plants might not be able to photosynthesize at all for months, and could kill plants that are vulnerable to frost. Rain and gravity will remove the dust in a few years, just as it does the ash from

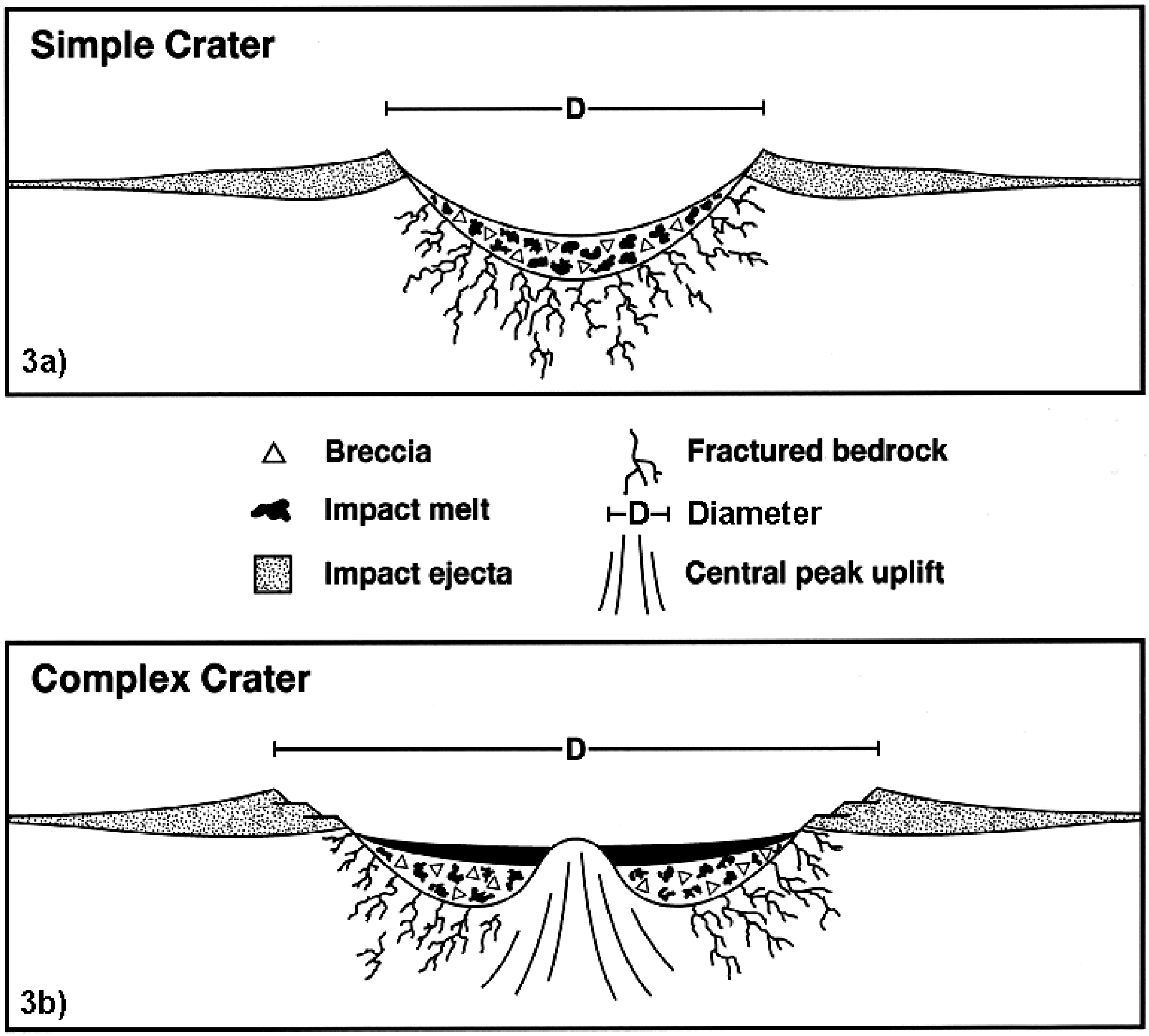

Figure 3: Diagram showing a cross-section of a) a simple crater and b) a complex crater. Modified from http://craters.gsfc.nasa.gov/assests/images/craterstructure.gif

a stratovolcano. But a few years of impact winter will have destroyed vulnerable populations of large animals that cannot migrate or go without food for months at a time. Herbivores would starve first, then carnivores.

Impact winter has nothing to do with the Pleistocene ice ages when wooly mammoths and saber-toothed tigers roamed the Northern Hemisphere. During a Pleistocene ice age, climate cooled gradually over tens of thousands of years. Also, the Pleistocene ice ages only began between three and two million years ago. There is currently no evidence for glaciers or ice sheets anywhere on Earth at the end of the Cretaceous or afterwards for millions of years.

Impact Structure	Age (millions of years ago)	Original Crater Diameter (km)	Associated Extinction Event
Barringer Crater (W. U.S.)	0.05	1.25	none
Ries Crater (Germany)	14	24	none
Chesapeake Bay (E. U.S.)	35	85	none
Popigai	36	100	none
Chicxulub (S.E. Mexico)	66	180	end-Cretaceous
Lac Manicouagan (cental Canada)	214	100	none
Sudbury (Canada)	1,850	250	unknown
Vredefort Dome (S. Africa)	2,000	300	unknown

Table 1: Characteristics of several well-known impact sites.

Most verified massive impacts are not associated with a mass extinction event, or even a minor extinction. However, the largest crater less than a billion years old dates from the end of the Cretaceous (near Chicxulub, Mexico). Smaller impacts may not add enough debris to the atmosphere to cause a really devastating impact winter. Also, there are no verified large craters the same age as the four older major mass extinctions. However, craters tend to fill with sediment over time, and their rims and central uplift areas are vulnerable to erosion. Older craters in the ocean are likely to have been subducted into the mantle as part of the process of plate tectonics. Still other potential impact craters cannot be examined by geologists. For example, there is a large structure, possibly a huge compound crater, in Wilkes Land, Antarctica, but it is under several kilometers of ice.

What is the Evidence for a Massive Impact at the End of the Cretaceous?

In 1980, when Luis and Walter Alvarez proposed that an asteroid impact had started the chain of cause and effect that led to the end-Cretaceous mass extinction, only a few craters had been verified as impact structures. Cryptovolcanism had not yet been rejected by the scientific community. Walter Alvarez had been studying a layer of sediment deposited 66 million years ago, during the end-Cretaceous mass extinction, and found it to be highly enriched in iridium. Iridium is rare on Earth, but more common in asteroids. Therefore, they argued, a lot of extraterrestrial matter, dozens of times more than usual, had been deposited on Earth's surface from the atmosphere over a short period of time. Alvarez et al. (1980) assumed the meteor's iridium-rich dust had been spread roughly evenly across the world and that the meteor was of the most common class we see today. They worked backward from the amount of iridium that they had measured, and estimated that the meteor that it came from would have been 10 km across and the dust would have blocked much of the sunlight that would ordinarily have reached Earth's surface.

Geochemists began to test end-Cretaceous sediments from all over the world, and generally found remarkably high levels of iridium at the boundary between the Cretaceous Period and the Cenozoic relative to older and younger layers, supporting the Alvarez' impact-winter hypothesis. Paleontologists found relatively abrupt decreases in the diversity of shells of photosynthetic plankton in marine sediments from the end of the Cretaceous, indicating a food-web collapse. End-Cretaceous sediments are also enriched in soot. This soot originated from wildfires triggered by the heat of the impact but were spread through the atmosphere by the blast wave from impact.

However, critics of the Alvarez hypothesis pointed out that an impact that severe should have left a spectacular crater. It took over ten years for the geologic community to rediscover the impact structure at Chixculub in Mexico. It’s a large structure, but nearly invisible even from the air because it is mostly underwater and has filled with sediment over time. In the 1960s and 1970s, oil geologists discovered Chicxulub Crater but it took decades for them to persuade Pemex, the oil company they worked for, to let them share their data and gather evidence that would eventually show it had been caused by an asteroid impact.

In the late ‘80s, the Alverez’ colleagues had found shocked quartz and tektites in several end-Cretaceous deposits in the Caribbean. Tektites are glass droplets formed by molten rock ejected from an impact crater. So they started to consider a shallow marine impact, which would still fill the atmosphere with iridium-rich dust, somewhere in that area. In 1990, Carlos Byars, a reporter, finally brought members of the two communities together.

The Deccan Traps erupted from 67 to 63 million years ago in India. These enormous volcanic eruptions lasted for millions of years and are still thought by many scientists as playing a major role in the end-Cretaceous extinction. During the 1980’s, when there was still doubt about whether there had been a massive impact 66 million years ago, several scientists suggested that the iridium in the end-Cretaceous sediments was actually of volcanic origin, but even lava does not contain as much iridium as end-Cretaceous sediments in many areas. Geologists who prefer the Deccan Traps as the main cause of the end-Cretaceous extinction have also pointed out that we have large impact craters that are not associated with mass extinctions (including most of those on Table 1).

It is important to note that massive impact has never observed directly by humans. Much of what we know about the possible effects is based on evidence from past impacts, impacts on other solar-system bodies like the moon, and from models.

Acknowledgements

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