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A POST-IMPACT DEEP FREEZE FOR DINOSAURS

New research supports the hypothesis that dinosaurs were done in by climate change after an asteroid impact kicked up a massive plume of sulfur gases that circled the globe.

An artist's rendering of North America in the weeks following the Chicxulub impact shows freezing conditions and skies hazy with sulfate aerosols. The pair of T. Rex *chicks in the foreground survived the impact but will soon succumb to the cold. Credit: @JamesMcKay-Creative Commons*

BY AUBREY ZERKLE

One balmy spring day 66 million years ago, a space rock 100 times the size of the International Space Station hurtled into what is now the southeastern tip of Mexico. The impact vaporized massive amounts of seawater and sulfur-rich marine rocks, creating a cloud of dust and aerosols that blanketed Earth and obscured the Sun.

This event, the Cretaceous-Paleogene (K-Pg) asteroid impact, remains one of the highest-profile cosmic disasters in Earth's history—it coincided with a planetwide extinction event that decimated nonavian dinosaurs and wiped out more than three quarters of life on Earth. The long-term biological consequences of this event are well established—the ecological reorganization that followed signified an end to the Mesozoic Age of Reptiles and ushered in the Cenozoic Age of Mammals.

The long-term environmental consequences of asteroid impacts remain foggy, but new fingerprints from atmospheric sulfur may help cut through the haze. Isotopic analyses of rock samples from Texas yielded clues to the history of the sulfur they preserved for posterity. Did the sulfur reach the stratosphere, and if so, did it stay there long enough to severely affect the climate?

The Chicxulub Impact

In 1980, geologist Walter Alvarez and his father, Luis, a Nobel Prize–winning physicist, first proposed that a collision with an extraterrestrial object wiped out the dinosaurs. The father-son team discovered up to 160 times the normal amount of iridium, an element sourced from cosmic dust, in deep-sea sediments formed at the same time as the extinction event. They suggested that the dust originated from a massive asteroid that smashed into Earth, explaining both the astonishingly high iridium levels and the coinciding extinction.

This sensational theory was met with skepticism for more than a decade, until 1991, when geophysicists discovered a circular structure about the size of Hawaii buried beneath the seafloor of the Yucatán Peninsula (Figure 1). Geochronologists dated melted glass in the walls of the structure and confirmed that it was roughly the same age as the mass extinction event. The crater was named Chicxulub, after the town closest to its center.

Paleontologists and geochemists set to work over the ensuing decades, scrutinizing the crater and impact ejecta in search of clues to the events that followed. They concluded that the impact caused a shock wave that wiped out everything in its immediate path, followed by devastating tsunamis and extensive wildfires. Tsunami waves propagated up rivers and onto land, producing landslides that buried anything in their path, including intact fish with well-preserved ear bones that constrained their time of death to Northern Hemisphere spring [*During et al.*, 2022].

These studies paint a terrifying picture of the devastation that occurred in the first few hours to days after the impact, but the immediate effects appear to have been too short-lived and localized to permanently alter Earth's biosphere. Some additional form of rapid and profound environmental disturbance must have occurred to cause widespread ecosystem upheaval in the decades that followed. But what are the long-term global consequences of a high-velocity planetary collision?

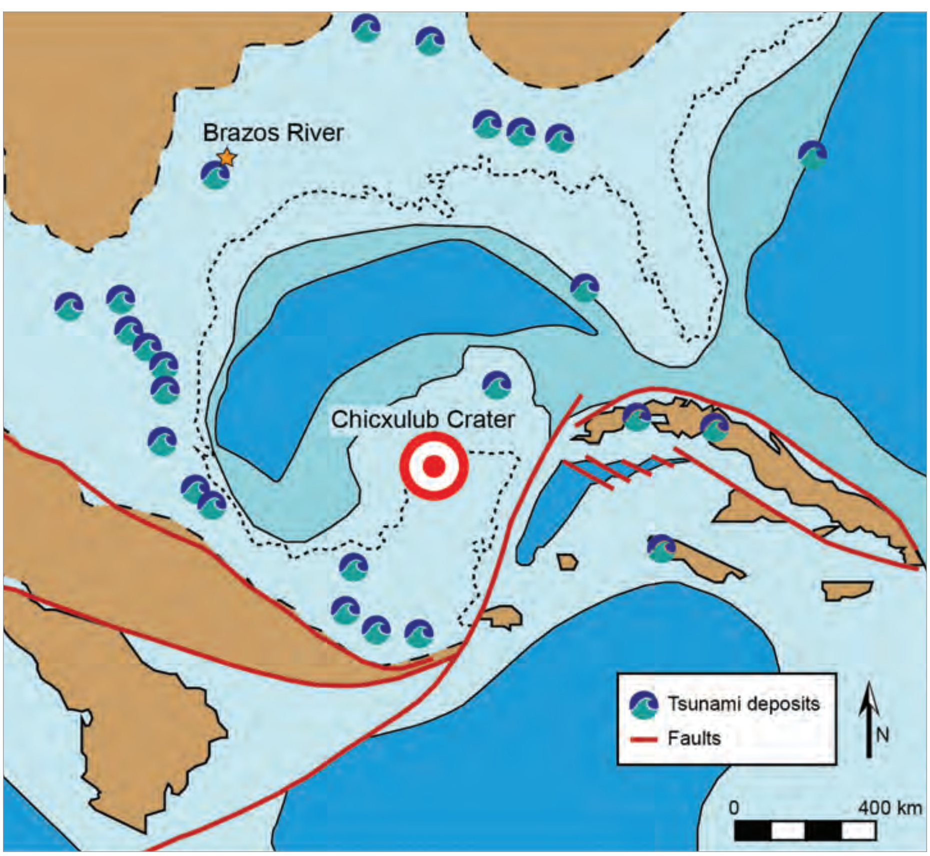

Fig. 1. A map of the Gulf of Mexico at the end of the Cretaceous, showing the relationship between the Brazos River deposits (orange star) and the Chicxulub impact site (bull's-eye). Modified from Vellekoop et al. *[2014]*

Impact Winter

Extreme cooling associated with an "impact winter" has been proposed to explain the severity of the K-Pg mass extinction. In this hypothesis, the impact produced a cloud of dust and soot that temporarily blocked out the Sun, shutting down photosynthesis and sending global temperatures plummeting. Life on a frozen, desolate tundra would have been particularly challenging for land-based creatures acclimated to the warm, stable climate of the Late Cretaceous.

Calculations have confirmed that dust and soot could have blocked sunlight almost entirely, but these heavier particles would have rained out of the atmosphere in months to years rather than decades [*Tabor et al.*, 2020], limiting their effects to several chilling summers. The key to sustaining a long-term impact winter might lie in where the asteroid hit.

The Yucatán in the Late Cretaceous was like it is today, with warm, shallow seas overlying a sulfur-rich carbonate platform. Volatilization of these rocks during the impact would have injected massive loads of carbon dioxide,

(left to right) Linda Ivany, Christopher Junium, and James Witts examine the main K-Pg boundary deposit at Darting Minnow Creek near the Brazos River in Texas. Credit: Shiv Das

sulfur, and other climatically active gases into the atmosphere. In particular, atmospheric sulfur rapidly forms sulfate aerosols, which can reflect incoming solar radiation and cool the planet for many years after an impact-generated plume has dissipated.

Geochemists recently confirmed that rubble collected from the Chicxulub crater contained virtually no sulfur [*Gulick et al.*, 2019], meaning that all the sulfur in these rocks, with an estimated mass of more than 10 million times that of the Eiffel Tower, must have been vaporized into the atmosphere. However, sulfate aerosols have long-term climatic effects only when they form in the stratosphere, where they can remain for years to decades.

This altitude dependence complicates attempts to model the global cooling effect of the Chicxulub impact because the height of the plume depends on unknowns like impact angle and velocity. Direct, empirical data are needed to test how much sulfur reached the stratosphere, where it would have caused the maximum disturbance.

Atmospheric Fossils

Fortuitously, the interaction of sulfur gases with ultraviolet (UV) light produces a unique geochemical signature, termed mass-independent fractionation of sulfur isotopes, or MIF. As the name suggests, MIF refers to chemical or physical processes that separate the isotopes of an element. “Mass independent” indicates that the amount of difference in the masses of the isotopes does not determine the degree of isotope separation.

Until recently, sulfur MIF signatures have been found only in rocks that formed more than 2.3 billion years ago, when Earth’s atmosphere was devoid of oxygen. The reason is that today, molecules of oxygen in our atmosphere combine to produce a stratospheric ozone layer, which blocks most harmful UV rays from reaching Earth’s surface, preventing them from burning our skin and damaging our DNA. This protective shield also blocks UV light from interacting with any sulfur gases emanating from volcanoes and hot springs, which rain or fall out of the lower atmosphere with no MIF.

I’ve spent much of my career examining these rocks, with their isotopic signatures preserved like ancient atmospheric fossils, to determine how and when oxygen built up on Earth. If the Chicxulub impact thrust huge amounts of sulfur above the ozone layer and into the stratosphere, the sulfur in these rocks should contain similar MIF signatures. A collaboration with my close friend and colleague Christopher Junium, from Syracuse University, provided some valuable insights.

DIRECT, EMPIRICAL DATA ARE NEEDED TO TEST HOW MUCH SULFUR REACHED THE STRATOSPHERE, WHERE IT WOULD HAVE CAUSED THE MAXIMUM DISTURBANCE.

In early 2019, Chris, along with James Witts and Linda Ivany, visited the Brazos River area, in Texas, to sample a section of rocks across the K-Pg boundary. The team's original goal was to collect the shells of Late Cretaceous ammonites (now extinct sea creatures with spiral shells) to reconstruct their diets, but the researchers also collected a full suite of samples across the section.

THESE DATA DEFINITIVELY SHOWED THAT SULFUR FROM THE IMPACT EVENT WAS THRUST INTO THE STRATOSPHERE, WHERE IT WOULD HAVE PROLONGED GLOBAL COOLING AND INTENSIFIED THE EXTINCTION.

This careful sampling proved key to our later work. The K-Pg event deposits that they collected in the Brazos River area constitute an expanded sequence of tsunami or storm deposits with exceptional temporal resolution, perfect for capturing such a geologically fleeting event. And most exciting, the rocks contained oodles of sulfur, with up to 10 times more sulfur in the impact deposits than in the rocks formed just prior to impact!

Chris had already received a fellowship to visit my lab at the University of St Andrews later that spring, and we decided to have a go at analyzing MIF in his samples to search for evidence of stratospheric sulfur. More serendipity followed, as the first sample we measured contained the largest MIF signal we found, spurring us on.

In fact, all the impact deposits that we analyzed showed signs of MIF. Perhaps more important, none of the samples from before or after the impact did. When the COVID-19 pandemic shut down labs in early 2020, I set about testing various mixing models to see whether any normal marine processes could explain the sulfur isotope data from the Brazos impact deposits. In the end, the only way to reproduce these signals was by dropping a massive load of MIF-bearing sulfur onto the Late Cretaceous continents and ocean [*Junium et al.*, 2022].

These data definitively showed that sulfur from the impact event was thrust into the stratosphere, where it would have prolonged global cooling and intensified the extinction. Further MIF analyses of additional K-Pg rocks from around the world should help confirm the extent of the sulfur plume and the duration of the resulting impact winter. Comparison with a more recent event offers additional clues. In 1991, the eruption of Mount Pinatubo released sulfate aerosols into the stratosphere. This event released about 100,000 times less sulfur than the Chicxulub impact, but it still caused global temperatures to decrease by 0.5°C for 2 years.

The Next Big One

Asteroid impacts constitute the single greatest unavoidable threat to life on Earth—the K-Pg event was the most recent, most deadly point of comparison. As of June 2022, NASA's Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) has detected 849 near-Earth asteroids with a diameter of 1 kilometer or greater. The full list of near-Earth objects (NEOs) currently contains 13 objects with an impact probability of 1 in 10,000 or higher, the largest of which is a half kilometer in diameter, about 5% the size of the Chicxulub asteroid.

In 2021, NASA launched its first large-scale planetary defense test mission, the Double Asteroid Redirection Test (DART). The DART mission became the first to successfully alter the path of an NEO in space as it completed a collision course with the asteroid Dimorphos in September 2022. DART laid the groundwork for the development of similar technology for defending Earth against small-scale impacts.

But what will happen when the next big one approaches our humble planet? For *Tyrannosaurus rex* and its feathered friends, it seems that survival options were limited—they either died quickly in a fiery inferno or slowly froze and starved to death in the harsh decades-long winter that followed. If "forewarned is forearmed," perhaps humanity's new knowledge will offer us a broader range of options.

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