Death of the DINOSAURS

DOUGLAS HENDERSON

From the ashes, a new view of the dinosaurs' final days

By Thomas Sumner

Below the shimmering turquoise waters of Mexico's Yucatán Peninsula lies the scene of a prehistoric mass murder. In a geologic instant, most animal and plant species perished. Drilling through hundreds of meters of rock, investigators have finally reached the footprint left by the accused: Earth's most notorious space rock impact, Chicxulub. The dinosaur killer.

Sleuthing scientists are assembling the most detailed timeline yet of the dinosaur apocalypse by giving fresh scrutiny to telltale fingerprints left by the fateful event 66 million years ago. At the impact site, mountains formed in mere minutes where an asteroid (or maybe a comet) crashed onto Earth's surface, the new work reveals. In North America, towering tsunamis buried plants and animals alike under thick piles of rubble. Around the world, skies darkened by the resulting debris chilled the planet for years.

But the asteroid may not have acted alone. Life may have already been in trouble. Growing evidence points to a supervolcanic accomplice (*SN: 1/10/15, p. 12*). Outpourings of molten rock and caustic gases in what is now India may have acidified the oceans and destabilized ecosystems long before and after the Chicxulub impactor hit. The jolt of the impact may have even boosted the eruptions, some researchers argue.

As more clues have been uncovered, many of them conflicting, the identity of the dinosaurs' true killer — impact, volcanism or both — has become less clear, says Paul Renne, a geoscientist at the Berkeley Geochronology Center in California.

"As we've improved our understanding of the timing, we haven't resolved the details," Renne says. "The last decade of work has only made it harder to distinguish between the two potential causes."

The smoking gun

What is clear is that a massive die-off took place around this time. It is visible in the layers of rock. One of the starkest changeovers in that planetary record marks the boundary between the Cretaceous and Paleogene periods some 66 million years ago (previously known as the Cretaceous-Tertiary or K-T). Studies of fossils found (or not found) across that K-Pg boundary reveal that about three-quarters of plant and animal species went extinct — from the ferocious *Tyrannosaurus rex* to microscopic plankton. Everything living on Earth today traces its ancestry to the few lucky survivors (see Pages 22 and 26).

Over the years, scientists have blamed many suspects, from global plagues to a planet-frying supernova, for this catastrophic die out. In 1980, a team of researchers including father-son duo Luis and Walter Alvarez reported discovering abundant iridium in places worldwide along the K-Pg boundary. Iridium is rare in Earth's crust, but the metal is abundant in asteroids and other space rocks. The finding was the first hard evidence of a killer meteorite impact. But without a crater, the hypothesis couldn't be confirmed.

Piles of impact debris led crater hunters to the Caribbean. Eleven years after the Alvarez paper, scientists at last identified the smoking gun — a hidden crater circling the coastal Mexican town of Chicxulub Puerto. (The crater actually had been discovered in the late 1970s by oil company scientists, who used variations in Earth's gravitational tug to visualize its 180-kilometer-wide crater outline. Word of that find, however, didn't reach crater hunters for years.) Based on the gaping size of the depression, scientists estimate that the impact released 10 billion times as much energy as the nuclear bomb dropped on Hiroshima.

That's big, but questions have remained about how the impact might have caused so much death and destruction worldwide. To find answers, scientists recently returned to the scene of the crime.

Instant mountains

Reaching the Chicxulub crater itself takes effort. Tens of millions of years of sediment deposits now entomb the crater hundreds of meters underground, much of it below the seafloor. The solution, the *Myrtle* drilling vessel, looks a bit awkward cruising the ocean. Three colossal black cylinders rise from the deck like sailless masts, giving the ship a top-heavy look. Once in position, the ship transforms. The hulking cylinders drop to the seafloor and the ship jacks itself out of the water, standing tall on three legs like an oil rig.

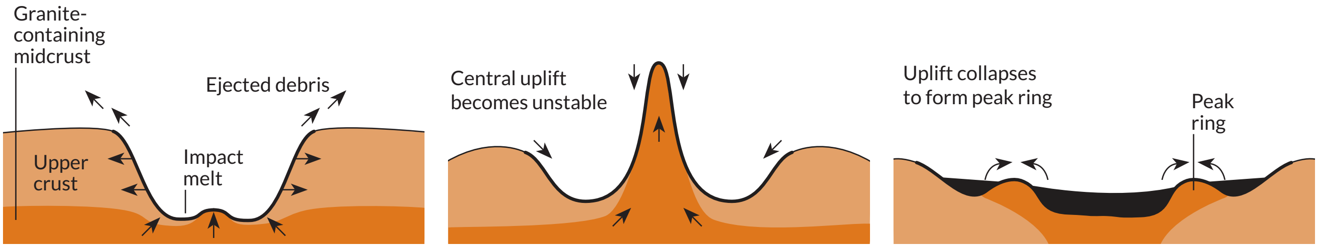
From this platform above the waves, scientists probed deep underground last April and May, to a halo of hills that tower hundreds of meters above the crater floor, about 30 kilometers off the Yucatán Peninsula. This peak ring formed in the aftermath of the impact and is the only one of its kind left on Earth. Getting hold of the rocky evidence locked inside the peak ring is key to understanding just how powerful the impact was.

In the process, the scientists recently resolved a mystery about how such large peak rings form. Simulations suggest that an impact s deep rocks to the surface, leaving the circle of peaks. Some scientists, though, argued that the ring had a less violent origin, forming from near-surface materials as the ground rebounded after impact. Confirming whether the computer simulations reflect reality required some seriously deep drilling, says Sean Gulick, a geophysicist at the University of Texas at Austin who co-led the expedition.

The team drilled 1,334.7 meters down from the seafloor over nearly two months at a cost of about $75 per centimeter. The effort proved worth it once the first impact-forged rocks from the crater itself were in hand, says Joanna Morgan, a geophysicist at Imperial College London and the project's co-leader. The rocks are "dramatic," she says, a kaleidoscope of black, green, red and white

Rocks collected from a ring inside the Chicxulub crater (intact core, left, and core fragment, right, with mineral deposits) contain granite of a type usually found at much greater depths, showing that the impact pushed deep rocks to the surface.

FROM LEFT: ARAE@ECORD_IODP; WUELBERS@ECORD_IODP



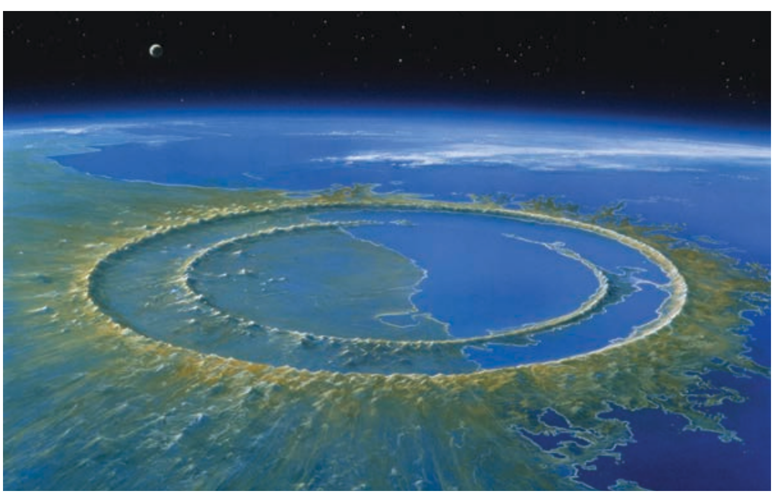
Ringing true The elevated ring inside large impact craters forms from deep rocks churned to the surface by the blast. In minutes, these rocks flow into the newly opened void, meeting in the crater's center as a single column (center) before collapsing outward and forming the peak ring structure. SOURCE: J.V. MORGAN *ET AL/SCIENCE* 2016

minerals including granite. "It looks like a fake kitchen countertop," Gulick says. "No other rock looks like this."

That granite solved the peak ring formation mystery even before the ship returned to shore. In the region, minerals such as granite are buried many kilometers below the surface in the midcrust. Finding abundant granite in the relatively shallow peak ring means the models were right: The force of the impact pushed deep material to the surface, the researchers reported in the Nov. 18 *Science* (*SN Online: 11/17/16*). That lifted material flowed into the newly opened wound in Earth's surface, meeting in a giant column at the crater's center before collapsing outward and forming the roughly 550-meter-tall peak ring — less than 10 minutes after impact.

Scientists will use the data collected by the Chicxulub drilling team to improve simulations to better estimate how much energy and debris the impact unleashed, says Ross Potter, a planetary scientist at Brown University in Providence, R.I. Getting those numbers right is important because the blast itself wasn't the big killer in the impact scenario. It was the darkness that followed.

A drilling expedition into the ring of mountains (inner circle) inside the Chicxulub crater (illustrated) suggests that simulations of the impact event are correct.



Inescapable night

The ground shook. Powerful gusts roiled the atmosphere. Debris rained from the sky. Soot and dust, spewed by the impact and resulting wildfires, filled the sky and began to spread like a giant sunlight-blocking shade over the entire planet. A new simulation gives researchers a better sense of just how long the darkness lasted; earlier estimates ranged broadly from just months to years.

The length and severity of the global cooldown was dramatic, says paleoclimatologist Clay Tabor of the National Center for Atmospheric Research in Boulder, Colo. He and colleagues assembled the most detailed computer simulation ever made of the impact's climate consequences, a sort of digital crime scene reconstruction.

The simulation begins with the preimpact climate, based on geologic evidence of ancient vegetation and levels of atmospheric carbon dioxide. Then comes the soot. A high-end estimate of released soot, based on the size and global fallout of the impact, is 70 billion metric tons, the weight of about 211,000 Empire State Buildings.

For two years, no light reached Earth's surface — any part of it, the simulation shows. Global temperatures plummeted by 16 degrees Celsius and Arctic ice spread southward, Tabor reported in September in Denver at the Geological Society of America's annual meeting.

Some areas would have been hit particularly hard, Tabor's work suggests. The equatorial Pacific saw dramatic drops in temperature while coastal Antarctica barely cooled. Inland areas generally fared worse than coastal areas. Those divides could help explain why some species and ecosystems weathered the impact while others didn't, Tabor says. Six years after the impact, sunshine returned to preimpact levels. Two years after that, land temperatures rose above preimpact conditions and the climate ultimately warmed several more degrees due to the insulating blanket of carbon sent airborne by the impact.

FROM TOP: J. HIRSHFELD; DETLEV VAN RAVENSWAAY/SCIENCE SOURCE

Evidence of the chilling darkness is in the rock record. Ancient microbes adapted to local sea surface temperatures by modifying the lipid molecules in their membranes. The fossilized remains of those lipids provide a temperature record, says Johan Vellekoop, a geologist at University of Leuven in Belgium. Fossilized lipids in what is now New Jersey suggest that temperatures there plummeted 3 degrees following the impact, he and colleagues reported in *Geology* in June.

Similar abrupt temperature drops plus darkened skies killed plants and other species that nourish the rest of the food web, Vellekoop says. "Dim the lights and the entire ecosystem collapses."

The cold darkness was the impact's deadliest weapon, but some unfortunate critters died too soon to witness it.

Buried alive

An ancient graveyard covers swaths of Montana, Wyoming and the Dakotas. Called the Hell Creek Formation, it's hundreds of square kilometers of paleontologist paradise. Erosion has left dinosaur bones jutting out of the ground, ready to be plucked up and studied. Here, in the dry badlands, thousands of kilometers away from the Chicxulub crater, paleontologist Robert DePalma of the Palm Beach Museum of Natural History in Florida found something surprising: signs of a tsunami.

Evidence of the supersized tsunami generated by the Chicxulub impact had previously been found only around the Gulf of Mexico — never this far north or so far inland. But the symptoms of tsunami devastation were clear, DePalma says. The rushing water dumped sediment onto the landscape. The debris originated from the nearby Western Interior Seaway that once cut across North America from Texas to the Arctic Ocean.

The sediment contained iridium and glassy debris formed from rock vaporized by the impact as well as fossilized marine species such as snail-like ammonites carried from the seaway. The macabre evidence didn't stop there.

"These are the dead bodies," DePalma said at the geological society meeting, pulling up slides of fish fossils found inside the tsunami deposits. "If a CSI team walks over to a burnt-out building, how do they know if the guy died before or during the fire? You look for carbon and soot in the lungs. In this case, fish have gills, so we checked those out."

The gills were packed with glass from the impact, which means the fish were alive and swimming when the asteroid hit. The fish remained alive, DePalma says, up until the moment the tsunami pummeled the landscape and crushed the fish under debris. Those unfortunate fish are the first known direct victims of the Chicxulub impact, he says. The ensuing climate change and deforestation took longer to do their damage.

The *Myrtle* drilling ship and its three towering legs offered a stable platform for scientists to drill into the crater left behind by the Chicxulub impact.

THE UNIVERSITY OF TEXAS AT AUSTIN JACKSON SCHOOL OF GEOSCIENCES

Just under the fish-filled tsunami deposits was another amazing find: dinosaur tracks from two species, says Jan Smit, a sedimentologist at VU University Amsterdam. "These dinosaurs were running and alive before they were hit by the tsunami," he says. "The entire ecosystem in Hell Creek was alive and kicking until the last moment. In no way was it on the decline."

The new evidence from the Hell Creek Formation confirms that most of the deaths at the time were caused by the Chicxulub impact, Smit argues. "I was 99 percent sure that it was the impact, and now that we've found this evidence, I'm 99.5 percent sure." While many other scientists share Smit's certainty, a growing faction doesn't. Emerging evidence supports an alternative hypothesis that the dinosaurs' demise came at least partly from deep within the Earth, not space.

Death from below

Long before the Chicxulub impact, a different disaster was mounting on the opposite end of the globe. The Deccan volcanic eruptions in India (at the time, a separate landmass near Madagascar) would ultimately belch about 1.3 million cubic kilometers of molten rock and debris. That's more than enough material to bury Alaska to the height of the world's tallest skyscraper. Gases spewed by similar volcanic outpourings have been linked to other major extinction events (*SN: 9/19/15, p. 10*).

After determining the ages of crystals embedded in the Deccan lava flows, researchers reported in 2015 that the bulk of the eruptions began roughly 250,000 years before the Chicxulub impact and continued for about 500,000 years after. The eruptions were raging at the height of the extinctions (*SN: 1/10/15, p. 12*).

This new timeline lends credence to those who doubt that the Chicxulub impact was the chief perpetrator of the extinction event. "Deccan volcanism is vastly more dangerous to life on Earth than an impact," says Princeton University paleontologist Gerta Keller. Recent research is showing just how detrimental. In the same way that iridium marks the fallout from the Chicxulub impact, the Deccan volcanism has a calling card of its own: mercury.

Most mercury in the environment originated from volcanoes. Large eruptions cough up tons of the element, and Deccan was no exception. The bulk of the Deccan eruptions released between 99 million and 178 million metric tons of mercury in total. Chicxulub released just a fraction of that.

All that mercury left a mark. In southwestern France and elsewhere, a research team discovered copious mercury in sediment laid down before the asteroid impact. Those same sediments held another clue as well: the fossilized shells of plankton from the dinosaur days. Unlike healthy shells, these specimens are thin and cracked, the researchers reported in *Geology* in February 2016.

These 65-million-year-old shells, *Cucullaea antarctica*, hold chemical clues of temperature change during the extinction event.

The fragmented shells suggest that CO_2 released by the Deccan eruptions made the oceans too acidic for some creatures, says Thierry Adatte, a geoscientist at the University of Lausanne in Switzerland who coauthored the study with Keller.

"Survival was getting very difficult for these critters," Keller says. Plankton form the marine ecosystem's foundation and their decline reverberated up the food web, she proposes. A similar trend is happening today as seawater soaks up CO_2 from fossil fuel burning. As waters become more acidic, the shell-making process requires more energy (*SN: 8/6/2016, p. 8*).

Partners in crime

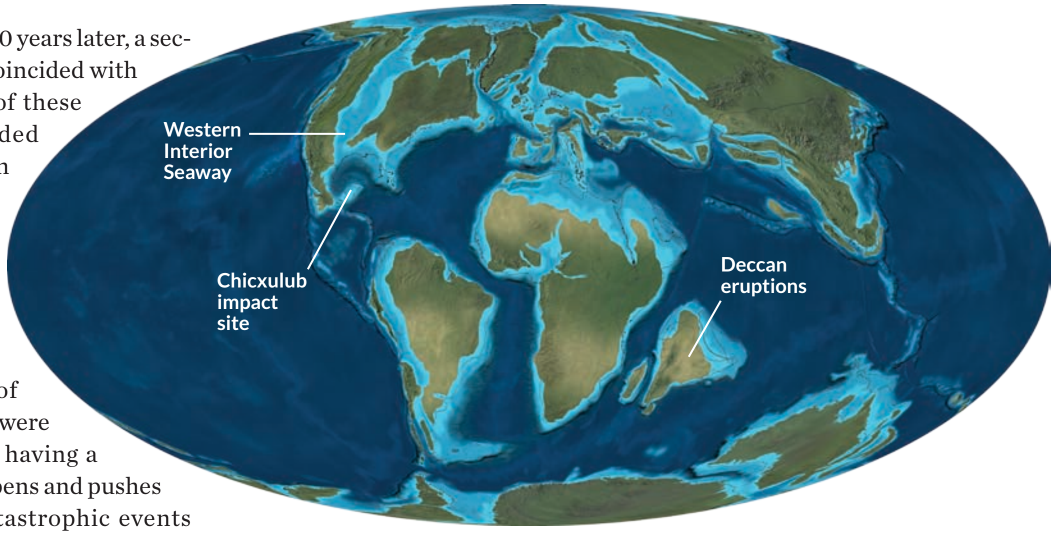
The Deccan eruptions wreaked havoc in at least part of Antarctica. Analyzing the temperature-dependent chemical makeup of the shells of 29 clamlike bivalves from the continent's Seymour Island, researchers assembled a roughly 3.5-million-year record of how Antarctic temperatures changed around the time of the dinosaur extinction. Following the start of the Deccan eruptions and the resulting rise in atmospheric CO_2, local temperatures warmed about 7.8 degrees, scientists from the University of Michigan and University of Florida reported in July in *Nature*

Deccan volcanic eruptions spewed more than a million cubic kilometers of molten rock and debris in what is now India. The outpourings, starting just before and running after the Chicxulub impact, may have contributed to the mass extinction that ended the reign of the dinosaurs.

FROM TOP: S.V. PETERSEN; MARK RICHARDS

Communications. About 150,000 years later, a second, smaller warming phase coincided with the Chicxulub impact. Both of these warming phases corresponded with high extinction rates on the island.

"Everyone wasn't just living happily, and then boom, this impact came out of nowhere," says study coauthor Sierra Petersen, a geochemist at the University of Michigan. Plants and animals "were already under stress and not having a great day, and this impact happens and pushes them over the top." Both catastrophic events were major contributors to the extinction event, Petersen argues. "Either one would have caused some extinction, but such a mass extinction is due to a combination of both events."



Double doomsday
Disasters unfolded across the world around 66 million years ago, from the Chicxulub impact in the Yucatán Peninsula, which sent tsunamis into the Western Interior Seaway, to the Deccan volcanic eruptions in India. These devastating events, imprinted in the rock record, altered the history of life on Earth.

Noting that some parts of the world were affected by the Deccan eruptions before the impact is "quite a jump" to demonstrating that life overall was stressed at the time, says Imperial College's Morgan. Fossil evidence in many regions suggests that marine life flourished until the impact, she says.

But maybe bad luck wasn't the reason the dinosaurs encountered two devastating disasters at once. Maybe the impact and the volcanism were in cahoots, some researchers propose. The idea isn't a scheme to get impact purists and the volcano devotees to play nice. Volcanic eruptions often follow major earthquakes, such as the 1960 Cordón-Caulle eruption in Chile that started two days after a nearby magnitude 9.5 quake. The seismic shock waves from the Chicxulub impact potentially reached magnitude 10 or above, Paul Renne says.

> "Everyone wasn't just living happily, and then boom, this impact came out of nowhere."
> **SIERRA PETERSEN**

Dating the Deccan lava flows, Renne and colleagues traced the intensity of the volcanism during the time of the impact. The volcanism continued uninterrupted for 91,000 years around the extinction event, Renne reported last April in Vienna at a meeting of the European Geosciences Union. The nature of the eruptions, however, changed within 50,000 years before or after the impact: Erupted material jumped from 0.2 to 0.6 cubic kilometers annually. Something altered the volcanic plumbing, he speculates.

In 2015, Renne and colleagues formally outlined their one-two punch extinction hypothesis in *Science* (*SN: 10/31/15, p. 12*). The shock of the impact fractured the rock enclosing the Deccan magma, the team proposed, allowing the molten rock to expand and possibly enlarging or combining magma chambers. Dissolved gases in the magma formed bubbles, which propelled material upward like a shaken soda can.

The physics behind this impact-volcano team-up is tenuous, scientists on both sides of the debate say, especially because Deccan and the impact site were so distant from each other. "This is all guesswork and perhaps wishful thinking," Princeton's Keller says. Gulick in Texas says the evidence isn't there. "They're hunting for another explanation when there's already an obvious one — the impact did it alone."

Over the coming months and years, improved simulations of the dinosaur doomsday and ongoing investigations of Chicxulub and Deccan rocks will add fuel to the deliberations. Ruling a definitive guilty verdict on either accused killer will be difficult, Renne predicts. Both events devastated the planet in similar ways at around the same time. "It's no longer easy to distinguish between the two," he says. For now, at least, the case of the dinosaur killer will remain an unsolved mystery. ■

Explore more

- Penny Barton. "Revealing the dynamics of a large impact." *Science*. November 18, 2016.
- Paul R. Renne *et al*. "State shift in Deccan volcanism at the Cretaceous-Paleogene boundary, possibly induced by impact." *Science*. October 2, 2015.