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OCTOBER 2021

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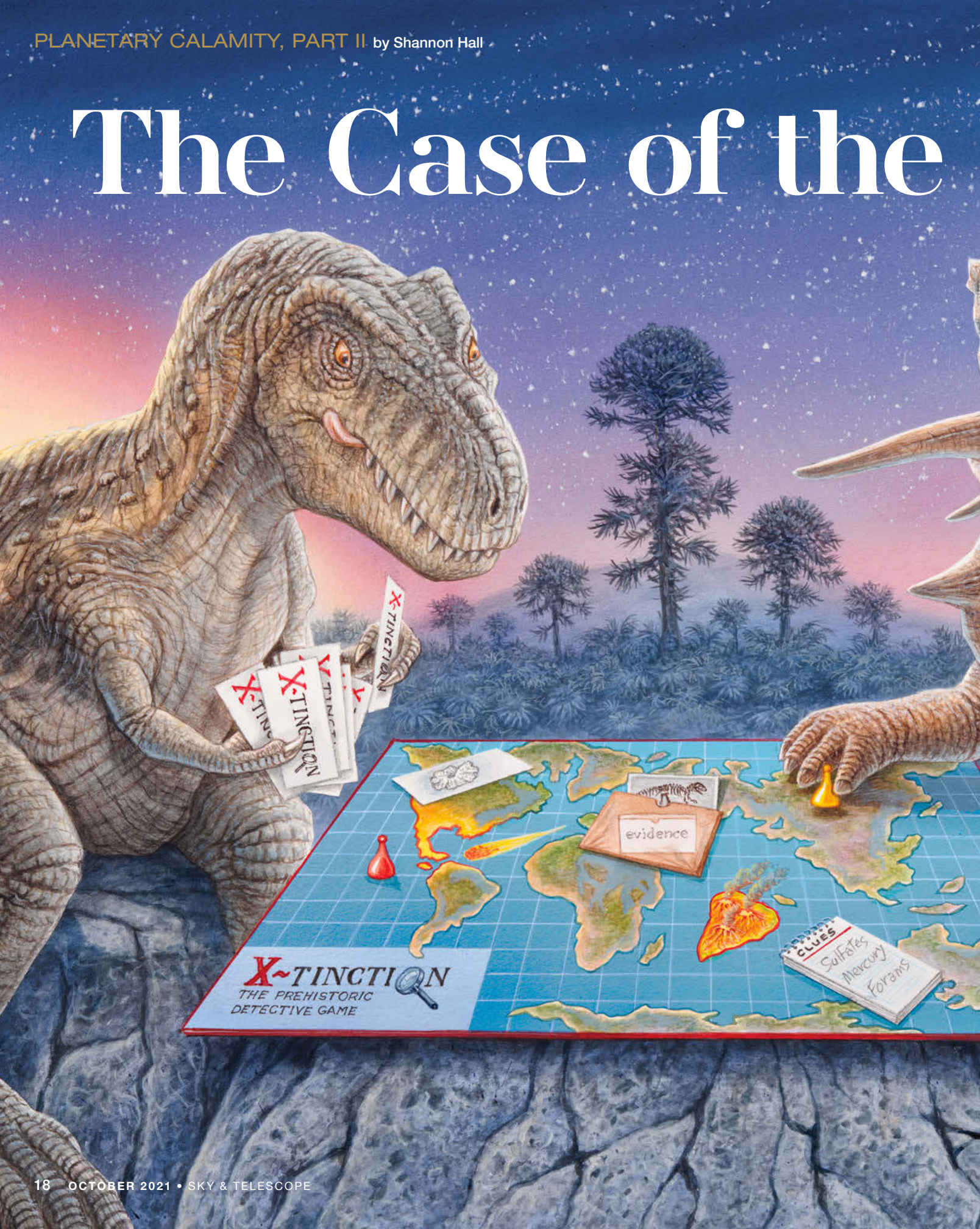
 by Shannon Hall

The Case of the



DEAD DINOSAURS

Scientists can't agree on whether an asteroid strike or volcanic eruptions caused the downfall of the dinosaurs.

It's the greatest whodunit in history. Roughly 66 million years ago, three-quarters of Earth's species — including the nonavian dinosaurs — were annihilated in a geological instant. The question is how.

Textbooks have long stated that the extinction occurred when a 10-km-wide asteroid (6 miles wide — larger than Mount Everest) slammed into the planet with a force of 10 billion atomic bombs. The punch would have unleashed a global darkness so powerful it shut down photosynthetic life and ultimately starved *T. rex* and its Late Cretaceous kin.

But the Hollywood scenario isn't as well accepted as it may seem.

At virtually the same time as the extinction, colossal volcanic eruptions smothered the Indian subcontinent in lava flows nearly twice as thick as the Grand Canyon is deep. Such an explosion would have belched enough carbon dioxide and other greenhouse gases into the atmosphere to raise the temperature on land and acidify the oceans — rendering the globe inhospitable. Thus some scientists argue that it was not an asteroid (or comet) but rather these volcanic eruptions that gave rise to the Age of Mammals.

And the debate is heated. Although recent improvements in rock-dating techniques, the hunt for toxic chemicals, and computer models are offering further clues, scientists remain divided. Yet the answer is crucial if we want to better understand such a dramatic event and shield the world from another mass extinction.

Death from the Skies

The asteroid theory took hold in 1980 when the Nobel Prize-winning physicist Luis Alvarez and three colleagues discovered an odd signature in the geologic record at the time of the extinction event: a layer of iridium. The element is rare in Earth's crust but common in meteorites, leading the team to conclude that a giant meteorite ended the Age of Reptiles.

The study created quite the wave. But there was one problem: Such a strike would have left a scar on Earth, and yet scientists had never discovered the culprit — until 1991. That's when scientists realized that a 200-km-wide bruise partially hidden below the Gulf of Mexico (and millions of years of marine limestone) dates back to the end of the Cretaceous Period.

ILLUSTRATION BY PHIL WILSON

CRIME SCENE RECONSTRUCTION: CHICXULUB

200-km-wide object **SLAMS** into present-day Mexico » Blast **INCINERATES** everything within roughly 1,000 km » Ejected CO_2 **ACIDIFIES** oceans, killing marine organisms » Sulfate aerosols **BLOCK** sunlight, global temperatures drop

Photosynthetic life decimated, disrupts food chain

But a better understanding of the cavity — and the mass extinction itself — has only been uncovered in recent years. In 2016, scientists used a lift boat, which traveled around the Gulf to a point midway out from the crater's center and then hoisted itself up above the water to create a platform. There it stayed for nearly three months as the team hung a drilling rig over the side and removed cores smothered in mud. Once they were cleaned, those cores revealed granite (similar to what you might find in a kitchen, but porous) beneath green and black breccia.

But there was one substance that was missing.

Earlier drilling performed on land had revealed that the area surrounding the crater was mostly composed of sedimentary rocks — including sulfur-rich evaporates. But the team found none of the evaporates in the rock cores. Instead, the hit likely ejected all of them into the atmosphere, where they vaporized and combined with water to create a dark haze of sulfate aerosols.

Those tiny particles, in turn, would have cooled the planet drastically. In fact, when scientists run climate models and release merely 100 gigatons of sulfur into the Cretaceous atmosphere, they find that the planet's temperature would have dropped 25°C (77°F). And it could be more drastic: Estimates from the drilling project are closer to 300 gigatons of sulfur.

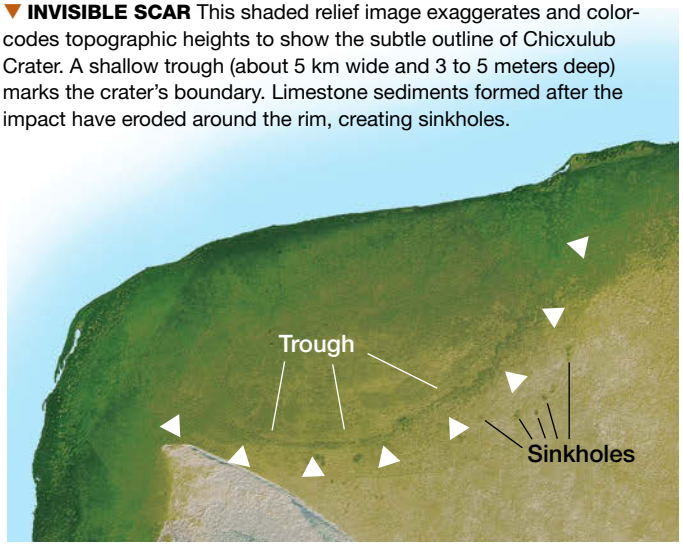
"The effect is remarkable to the planet," says Sean Gulick (University of Texas, Austin), who co-led the project. "On the order of 15 years, or even 20 years, there are close to freezing temperatures everywhere." Moreover, the aerosols would have plunged the globe into perpetual twilight, blocking enough sunlight to crush the global food chain.

The finding, combined with the geological record, led many scientists to conclude that they had caught the killer red-handed. If you look at the sediments running up to the extinction event, also known as the *K-Pg boundary*, most fossilized species vanish precisely at the iridium layer. "In every single section you look at all around the world, life is happy before the impact and then it's clearly devastated," says Joanna Morgan (Imperial College London), Gulick's co-leader.

The findings seemed so certain that many scientists turned their attention to debating the origins of the space rock (better known as the Chicxulub impactor). In 2007, astronomers argued that it was likely the result of a deadly collision beyond Mars. In 2013, a research team suggested that it was not an asteroid at all but a high-velocity comet, based on a new analysis of the chemical elements within the

◀ **CHICXULUB** A crater on the Yucatán Peninsula dates from 66 million years ago and is one of the largest known impact scars on Earth.

▼ **INVISIBLE SCAR** This shaded relief image exaggerates and color-codes topographic heights to show the subtle outline of Chicxulub Crater. A shallow trough (about 5 km wide and 3 to 5 meters deep) marks the crater's boundary. Limestone sediments formed after the impact have eroded around the rim, creating sinkholes.



ASTEROID: JOEBAKAL / SHUTTERSTOCK; MAP: GREGG DINDERMAN / S&T; CRATER GRAVITY MAP: NASA / JPL

> "In every single section you look at all around the world, life is happy before the impact and then it's clearly devastated." —JOANNA MORGAN

K-Pg boundary. That theory was put forth again in 2014 when physicists suggested that dark matter could have dislodged a comet and again this year when a different team argued the impactor was a fragment from an icy comet that flew too close to the Sun.

But these nuances aside, the impact theory is taught in astronomy and geology courses alike, and it appears in science museums across the globe and even in children's books. It is so well known, in fact, that if you were to take an informal poll at a party, everyone would likely say that it was an asteroid that spelled doom for the dinosaurs.

"The asteroid hypothesis is pretty much guaranteed at this point," Gulick says.

Fire and Ash

And yet there are scientists who deny the accepted dogma. When Gerta Keller (Princeton University) peers into the geologic record, she doesn't see a knife-sharp die-off coincident with the asteroid impact. Rather, she finds a gradual decline of fossils that began when volcanic eruptions across modern-day India belched greenhouse gases into the atmosphere.

The steady change appears across the globe. In the late 1980s, Keller analyzed rock sections in Tunisia and Texas to find that some populations of single-celled marine organisms called foraminifera started to decline 300,000 to 400,000 years before the impact. Her team released a similar story in 2012 when they discovered that plankton suffered severe losses early on. And in 2014, a separate team of scientists saw that some populations of amphibians at a site in Montana also dwindled before the asteroid struck.

"It may be presented as a closed book, but it's definitely not," says Courtney Sprain (University of Florida), who later worked on the Montana samples.

The culprit is obvious to Keller. Travel to India and you will see soaring plateaus and river canyons carved out of basalt — volcanic deposits known as the Deccan Traps that erupted at the end of the Cretaceous. In 2008, Keller's team determined that the lava flows preceded the extinction, but their exact timing has long been a crucial question. So from 2013 to 2016, Keller and her colleagues made several trips to Pune, India, where roads have been carved into the Traps — revealing layer atop layer of lava flows and providing a peek into their history. Her team cut samples from the lithified windborne ash that was occasionally sandwiched between the lava layers and sent the rocks home.

Back in the lab, they dated crystals within the ash to find that there were four distinct pulses of eruptions, with the biggest occurring merely tens of thousands of years before the extinction. Those results, published in 2019, help to paint a different picture of the extinction event. Add in both the fact that species were clearly stressed during that time and a discovery in 2018 that the global temperature increased once the Deccan Traps kicked into action, and it looks like the dinosaurs' fate was sealed long before the asteroid bore down on Earth.

It sounds wild, but it isn't unprecedented. On four other occasions, animal life has been nearly destroyed in planet-wide extinctions — all of which potentially came after volcanic eruptions.

◀ IMPACT DEBRIS Taken from about 650 meters below the seafloor in the Gulf of Mexico, this core contains suevite, a rock composed of fragments of limestone and granite as well as impact-made melt, all mixed together when the crater formed.

DRILLING IN CHICXULUB Researchers used the liftboat *Myrtle* to drill into Chicxulub Crater in 2016. In this location, the ocean is about 18 meters deep; the boat was raised about 15 meters above water level, to shield it from buffets by currents and tides during drilling.

JOANNA MORGAN (2)

CRIME SCENE RECONSTRUCTION: DECCAN TRAPS

1 million km^3 of lava **ERUPT** in multiple pulses in what is today India » Eruptions **SURGE** about 300,000 years before asteroid impact » Released CO_2 **RAISES** global temperatures a few degrees Celsius, peaking 200,000 years before impact » CO_2 **ACIDIFIES** oceans, killing marine organisms » Sulfate aerosols **BLOCK** sunlight, global temperatures drop

Photosynthetic life decimated, disrupts food chain

The key is that these are no ordinary flare-ups, but giant floods of lava that smother entire continents, stacking up kilometers thick. There is simply no modern-day analogue. The largest detonation at Yellowstone, for example, unleashed 2,450 cubic kilometers of magma — enough to cover the entire lower 48 United States in 30 centimeters of lava. But the Deccan Traps unleashed roughly 1 million km^3, enough to cover the entire U.S. in nearly 125 meters of lava. Only one-third of the Space Needle would stand above the flood. "It's just beyond imagination," says Stephen Grasby (Geological Survey of Canada).

Even today, their force is undeniable. "As soon as I was in the Deccan province and looking up at all the lava flows, I kept thinking, 'There's no way this did nothing — this is huge,'" Sprain says. "It's four kilometers thick of lava. And it's all around you, and it's all your eyes can see for miles."

▼ **DECCAN TRAPS** These vast lava flows in India date to about 66 million years ago and in places pile some 2 km thick. Such *large igneous provinces* punctuate Earth's geologic history (see page 12) and are sometimes coincident with mass extinctions in the fossil record.

This magnitude, combined with the geologic record, convinces Keller that the volcanic eruptions acted as the lone offender. With more than 200 papers to her name, she argues that such colossal volcanic eruptions would have released enough carbon dioxide and methane to short-circuit the global climate — raising temperatures on land and acidifying the oceans until the microscopic organisms that formed the base of the food chain perished. Once those met their end, larger animals would have followed, causing the global ecosystem to collapse. The asteroid would have had little to do with it.

Partners in Crime

With so much data supporting both hypotheses, some scientists are beginning to accept that the asteroid and the volcanic eruptions might have colluded.

Consider a swerve in temperature. Fossil analyses indicate that the heat wave was immediately followed by a cold snap, causing some scientists to argue that the Deccan Traps first warmed the globe, then the asteroid cooled it down. It's that abrupt change, argues Paul Renne (University of California, Berkeley), that spelled disaster for the dinosaurs.

Both Morgan and Gulick agree that this is a possibility, but they argue that the main killer was certainly the asteroid. In other words, the Deccan Traps might have held Earth hostage, but the asteroid shot the gun.

Then again, maybe the Deccan Traps fired the shot under duress. In 2015, Renne, Sprain, and others put forth a curious hypothesis that suggested that the impact might have kicked the ongoing volcanism into high gear. Chicxulub's collision would have unleashed earthquakes so powerful, the researchers said, that they raced through the globe and triggered Deccan's most destructive pulses.

Earthquakes can send modern volcanoes into overdrive. The seismicity creates new cracks that allow magma to escape more easily, and it changes the chemistry of the magma. "The best way to visualize that, I think, is take a can of pop and shake it up and open it," Renne says. The gas that was dissolved in the liquid escapes, driving eruption. The same happens within the magmatic system.

The team found that after the asteroid struck Earth, the

SMOKE TEXTURE: KANOKPOLTOKUMHNERD / SHUTTERSTOCK; MAP: GREGG DINDERMAN / S&T

▲ **LAVA EVERYWHERE** Vast stacks of ancient lava flows tower over the landscape in western India, dwarfing human habitations. These flows erupted over several hundred thousand years leading up to the dinosaurs' extinction, but researchers disagree about the exact timing.

lava at Deccan did appear to go into overdrive. The orientation of the cracks switched direction, the chemistry of the lava changed, and the flows might have become thicker — potentially doubling in output. But Renne notes that the latter is not statistically significant; it's suggestive, but not definitive.

Blair Schoene (Princeton University), who was not involved in the study but worked on dating the Deccan Traps with Keller, is more skeptical, arguing that the error bars on the eruption rates are too large to support that conclusion. "I don't think that holds much water at this point," he says.

On four other occasions, animal life has been nearly destroyed in planet-wide extinctions — all of which potentially came after volcanic eruptions.

Regardless, both agree that the Deccan Traps and the impact each played some role in the Cretaceous downfall. "I don't see how you can escape that," Renne says. "We're still working on the details, but the basic brushstrokes are clear."

Heated Debate

And yet, some extinction scientists remain staunchly on one side or the other.

Take two papers published last year. In one, Pincelli Hull (Yale University) and her team analyzed cores drilled off the coast of Newfoundland and found no evidence for the Deccan Traps' effects. In theory, the eruptions should have acidified the oceans and dissolved any carbonate shells. But instead, the team found carbonates that were remarkably well preserved.

"We see an abundance of 'glassy' foraminifera with skeletons so pristine that they look like they died yesterday," says Richard Norris (University of California, San Diego), who coauthored the paper.

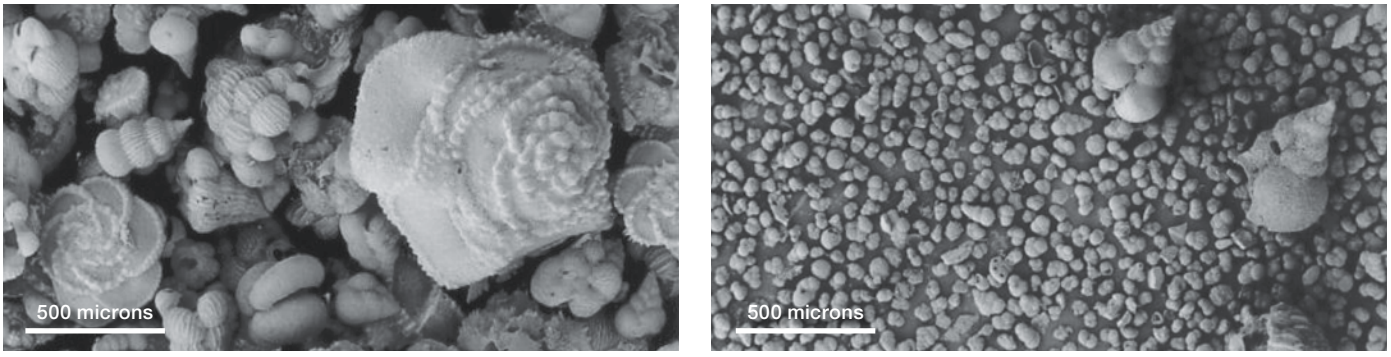
Yet the other paper suggests just the opposite. Keller's team discovered 20 different layers of mercury (a toxic metal released in volcanic eruptions) throughout the sedimentary record that coincided with an increase in temperature and (contrary to the Hull team's discovery) ocean acidification. "We have a cocktail — literally — of all the bad things that can typically end in a mass extinction," she says.

The mismatch might occur because digging through 66 million years of geologic history is, well, hard.

Remember the claim that species were dropping dead hundreds of thousands of years before the main extinction? That was based on a lack of fossils before the K-Pg boundary. Some scientists say the dearth could simply be a lack of data. On the other hand, any claim that species survived the impact would be based on fossils discovered after the K-Pg boundary — which could happen if some fossils had eroded out of an older formation and were redeposited to a younger one.

Ego might also play a role. "I mean, let's face it, a huge number of scientists in the U.S. are not just firm believers,

BLAIR SCHOENE



▲ **FORAMINIFERA** Before the K-Pg extinction event, deep-sea foram fossil specimens are large and diverse *(left)*. But after the extinction, large forams disappear *(right, note same scale)*. Abrupt environmental changes favor smaller organisms, which have more rapid life cycles and need fewer resources than larger organisms.

they've made their reputation on this — and nobody can possibly admit that they might be wrong," Keller says. "It's totally non-scientific."

And yet others would say the same about Keller. "She's made a career of being a contrarian," Norris says. "I think that her science is just driven by this idea that the impact was not the cause, and she sort of hunts around for evidence for that."

But Grasby, a leading expert on mercury who was not a coauthor on Keller's recent paper, was quite impressed by her latest work, arguing that the analysis is solid. In addition, it matches findings from the other major mass extinctions, which is promising — especially if you abide by Occam's razor, the philosophical idea that the simplest explanation is often the correct one.

Grasby is also grateful for the contrarian view. "I just appreciate that Gerta [Keller] is working hard to keep the debate going, and I think it's good for science to see some healthy active debate on these things," he says. "So it's good for her to be so doggedly pressing the cause."

33
BILLION TONS
CO_2 emitted by energy-related human activities *in 2019*

400
BILLION TONS
Estimated O_2 released *instantaneously* by Chicxulub impact

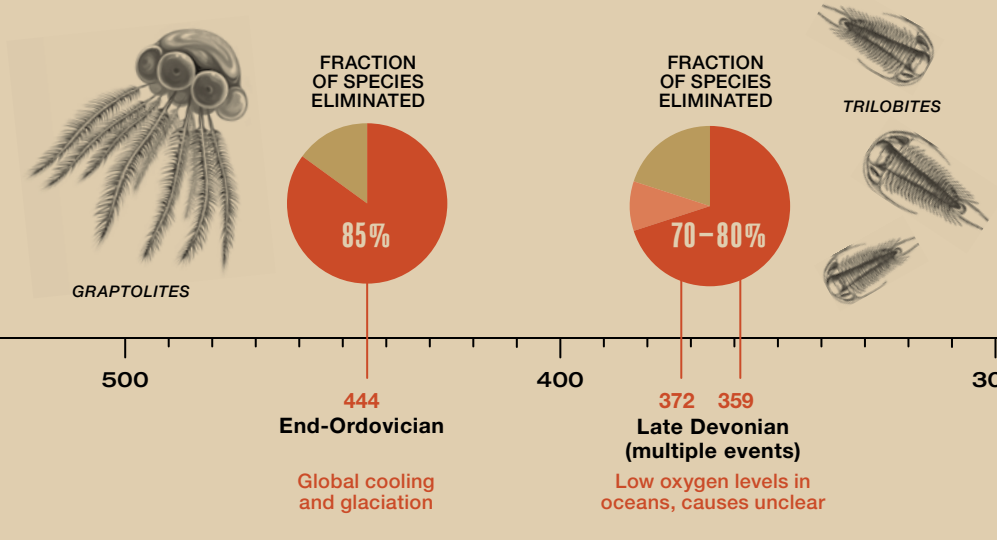
3,000–22,000
BILLION TONS
Estimated total CO_2 released by Deccan Traps, over *several hundred thousand years*

Indeed, many agree that the debate fuels progress, pushing experts to dig deeper — both literally and figuratively. And that is crucial if scientists want to avoid another global catastrophe.

The Chicxulub impact, for example, is sometimes upheld as the reason why we need to scour the skies in search of other life-threatening meteoroids. Although Keller argues that justification is overblown, there is no question that Chicxulub certainly wreaked havoc on the local ecosystem. "It is a preventable natural disaster, if you go look," says Amy Mainzer (University of Arizona). And NASA *is* looking. The Center for Near Earth Object

FORAMS: SCRIPPS INSTITUTION OF OCEANOGRAPHY / UNIV. OF CALIFORNIA, SAN DIEGO (2); TIMELINE: TERRI DUBÉ / *S&T*; GRAPTOLITES: LILIYA BUTENKO / SHUTTERSTOCK; TRILOBITES: MORPHART CREATION / SHUTTERSTOCK

MASS EXTINCTION EVENTS
Five major extinction events appear in Earth's fossil record. Some, like the Permian extinction (also known as "The Great Dying"), are clearly tied to volcanic eruptions; others' causes are still debated. There are dozens more smaller extinction events in the geologic record.



Studies at the Jet Propulsion Laboratory supports a number of teams that search for life-threatening objects, and this year a mission will launch designed to test technology that could change the trajectory of an impactor in space. Although astronomers have likely found 95% of kilometer-size asteroids, they've discovered only a third of the medium-size objects out there, Mainzer estimates. Those smaller ones would bring region-level devastation.

Volcanism is not so preventable. Renne argues that something like the Deccan Traps will almost certainly happen again: On average, these colossal volcanic eruptions occur roughly every 30 million years on land. The last one — which released the Columbia River flood basalts across Washington, Oregon, and Idaho — did most of its damage roughly 16 million years ago.

Yet Keller argues that the next mass extinction will not be caused by a volcanic eruption, but by us. And here, most scientists finally agree. Myriad data, from ice core studies to chemical analyses of our atmosphere's makeup, indicate that Earth's climate is warming today due to the greenhouse gases that we alone have emitted (see sidebar). Countless species are staring down extinction. But if scientists can use the findings from both the Chicxulub impact and the Deccan Traps to better understand how much strain terrestrial life can tolerate — specifically, the amount of greenhouse gases in the atmosphere — then they will have a much better idea of what to expect from the current crisis.

And that will help us truly focus on the defense of Planet Earth, Keller argues. "Scientists can already see the end of the world as we know it, not in thousands of years but just a few generations as we speed into the sixth mass extinction."

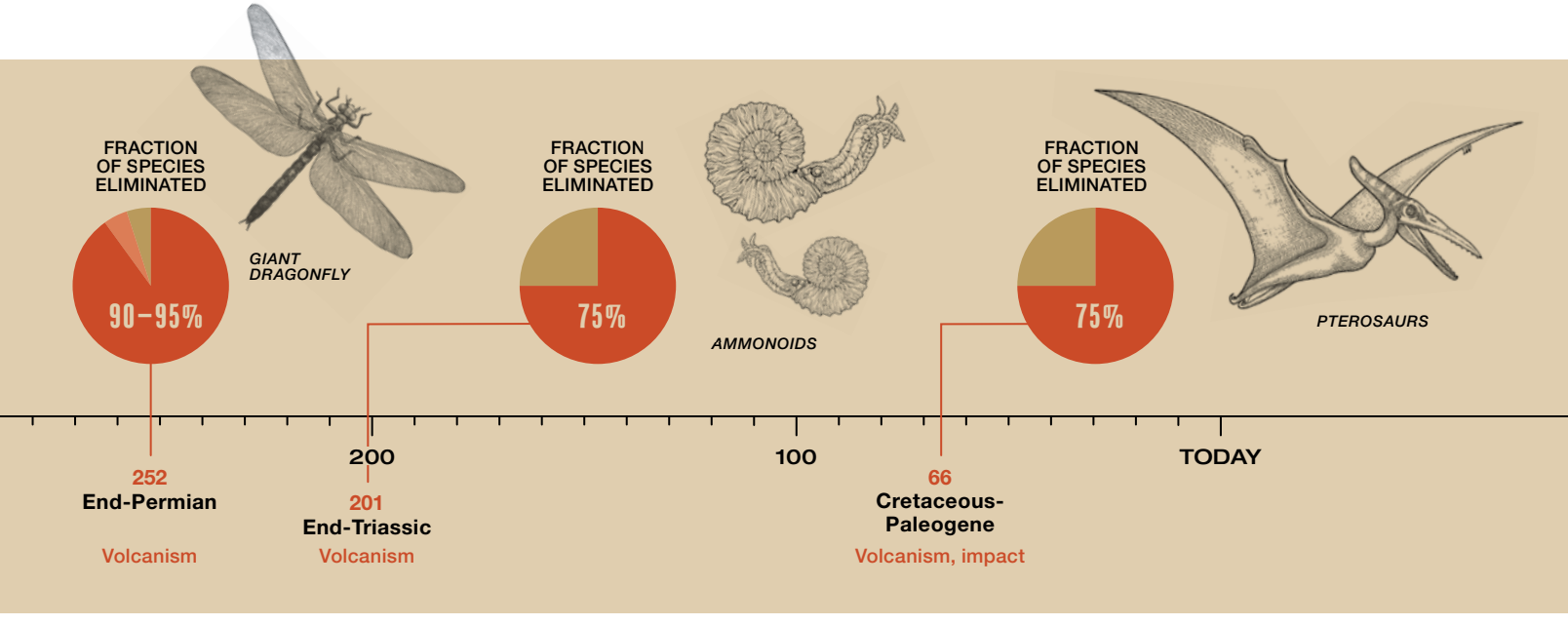
■ *S&T* Contributing Editor **SHANNON HALL** is an award-winning freelance science journalist who grew up traipsing around the Columbia River flood basalts in the Pacific Northwest.

CLIMATE CLIFF NOTES

While exactly how Earth's climate changed during the K-Pg extinction remains under debate, scientists do know that climate change today is both real and caused by human activity. Often omitted from discussions is *how* they know. Here are the key points leading to their conclusion:

- Air samples show that the atmospheric concentration of carbon dioxide (CO_2) is rising on Earth.
- CO_2 absorbs infrared radiation (heat). Adding more infrared-absorbing compounds, or *greenhouse gases*, to Earth's atmosphere throws off its energy balance and causes the planet to absorb more energy.
- This added energy should (among other things) raise the global average temperature, increase ocean temperatures, and spur more extreme weather. Absorbed CO_2 should also make the oceans more acidic. All are happening.
- Both modern and ancient air samples — the latter from air bubbles in ice cores reaching back several hundred thousand years — confirm that the CO_2 levels have spiked since the Industrial Revolution.
- The rate of atmospheric CO_2 increase matches that released by human activities for the same time period.
- The relative amounts of carbon's three isotopes — carbon-12, carbon-13, and carbon-14 — in the atmosphere will be different depending on where the carbon in the CO_2 comes from. Volcanoes and the burning of fossil fuels, for example, will lead to different proportions of carbon-13 and carbon-14 relative to carbon-12. Chemical analysis of Earth's atmosphere matches fossil fuels.

For a detailed discussion of these and other points, read Jeffrey Bennett's *A Global Warming Primer*. Find more information and resources for astronomers at **https://is.gd/astroclimate**. —*Camille M. Carlisle*



GIANT DRAGONFLY: ANDREY OLEYNIK / SHUTTERSTOCK; AMMONOIDS: ALZHAPARD / SHUTTERSTOCK; PTEROSAURS: KATRINE GLAZKOVA / SHUTTERSTOCK