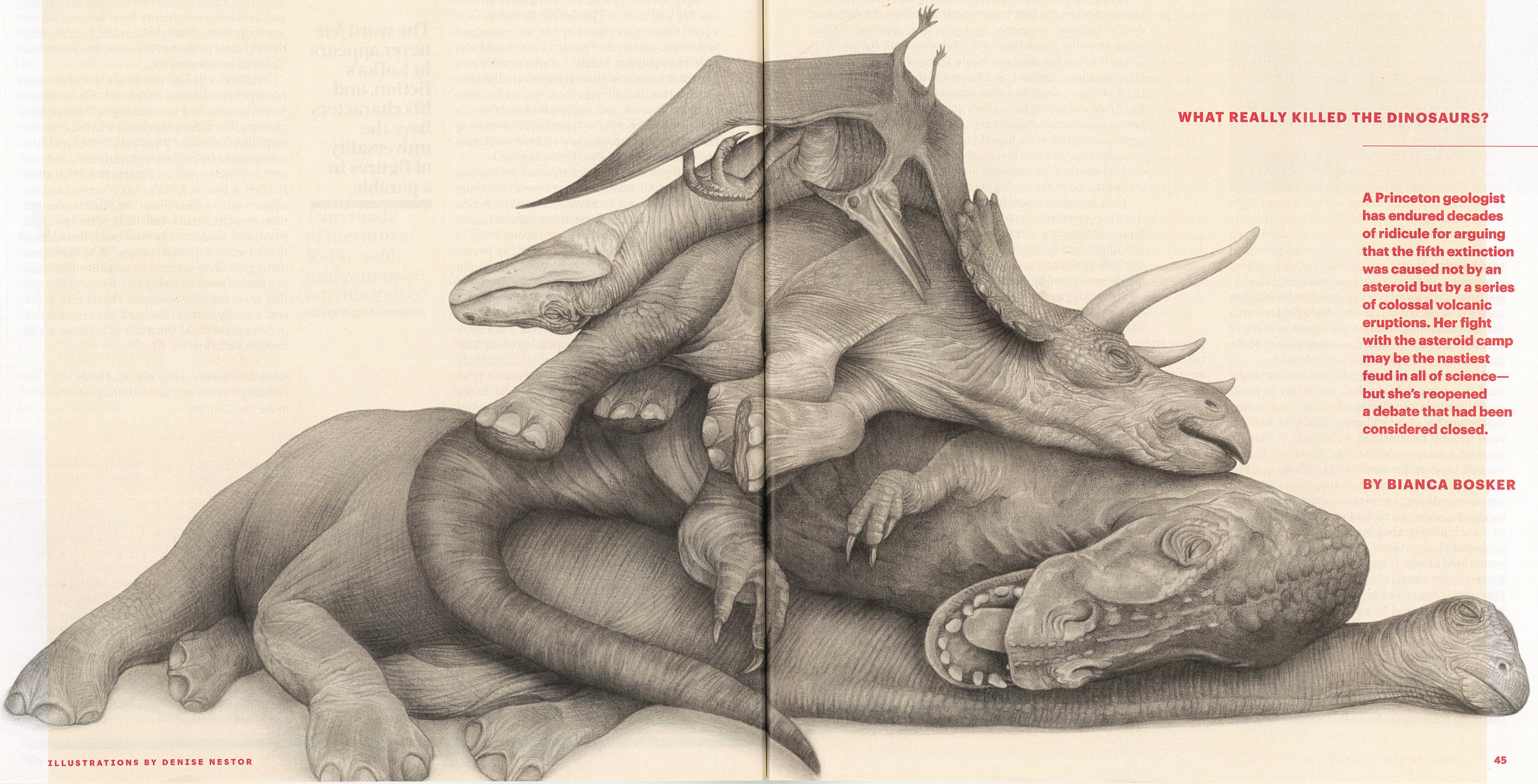
IMMEDIATE CAUSE
(Final disease or condition resulting in death)

a.

DUE TO (OR AS A CONSEQUENCE OF)

Interval Between Onset and Death

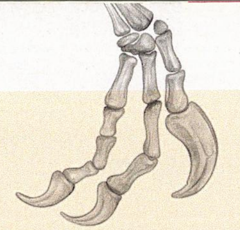


WHAT REALLY KILLED THE DINOSAURS?

A Princeton geologist has endured decades of ridicule for arguing that the fifth extinction was caused not by an asteroid but by a series of colossal volcanic eruptions. Her fight with the asteroid camp may be the nastiest feud in all of science—but she's reopened a debate that had been considered closed.

BY BIANCA BOSKER

ILLUSTRATIONS BY DENISE NESTOR



1.

GERTA KELLER WAS

waiting for me at the Mumbai airport so we could catch a flight to Hyderabad and go hunt rocks. "You won't die," she told me cheerfully as soon as I'd said hello. "I'll bring you back."

Death was not something I'd considered as a possible consequence of traveling with Keller, a 73-year-old paleontology and geology professor at Princeton University. She looked harmless enough: thin, with a blunt bob, wearing gray nylon pants and hiking boots, and carrying an insulated ShopRite supermarket bag by way of a purse.

I quickly learned that Keller felt such reassurances were necessary because, appropriately for someone who studies mass extinctions, she has a tendency to attract disaster. Long before our 90-minute flight touched down, she'd told me about having narrowly escaped death four times—once while attempting suicide, once from hepatitis contracted during an Algerian coup, once from getting shot in a robbery gone wrong, and once from food poisoning in India—and this was by no means an exhaustive list. She has crisscrossed dozens of countries doing field research and can claim near-death experiences in many of them: with a tiger in Belize, an anaconda in Madagascar, a mob in Haiti, an uprising in Mexico.

Keller had vowed not to return to India after the food-poisoning debacle. But, never one to avoid calamity, she'd traveled to Mumbai—and gotten sick before her plane had even landed; an in-flight meal had left her retching. Keller was in India to research a catastrophe that has consumed her for the past 30 years: the annihilation of three-quarters of the Earth's species—including, famously, the dinosaurs—during our planet's most recent mass extinction, about 66 million years ago. She would be joined in Hyderabad by three collaborators: the geologists Thierry Adatte, from the University of Lausanne; Syed Khadri, from Sant Gadge Baba Amravati University, in central India; and Mike Eddy, also from Princeton. They picked us up at the airport in a seat-belt-less van manned by a driver who looked barely out of his teens, and we began the five-hour drive to our hotel in a town so remote, I hadn't confidently located it on a map.

Where I looked out our van's window at a landscape of skeletal cows and chartreuse rice paddies, Keller saw a prehistoric crime scene. She was searching for fresh evidence that would help prove her hypothesis about what killed the dinosaurs—and invalidate the asteroid-impact theory that many of us learned in school as uncontested fact. According to this well-established fire-and-brimstone scenario, the dinosaurs were exterminated when a six-mile-wide asteroid, larger than Mount Everest is tall, slammed into our planet with the force of 10 billion atomic bombs. The impact unleashed giant fireballs, crushing tsunamis, continent-shaking earthquakes, and suffocating darkness that transformed the Earth into what one poetic scientist described as "an Old Testament version of hell."

Before the asteroid hypothesis took hold, researchers had proposed other, similarly bizarre explanations for the dinosaurs' demise: gluttony, protracted food poisoning, terminal chastity, acute stupidity, even *Paleo-weltschmerz*—death by boredom. These theories fell by the wayside when, in 1980, the Nobel Prize–winning physicist Luis Alvarez and three colleagues from UC Berkeley announced a discovery in the journal *Science*. They had found iridium—a hard, silver-gray element that lurks in the bowels of planets, including ours—deposited all over the world at approximately the same time that, according to the fossil record, creatures were dying en masse. Mystery solved: An asteroid had crashed into the Earth, spewing iridium and pulverized rock dust around the globe and wiping out most life forms.

Their hypothesis quickly gained traction, as visions of killer space rocks sparked even the dullest imaginations. NASA initiated Project Spacewatch to track—and possibly bomb—any asteroid that might dare to approach. Carl Sagan warned world leaders that hydrogen bombs could trigger a catastrophic "nuclear winter" like the one caused by the asteroid's dust cloud. Science reporters cheered having a story that united dinosaurs *and* extraterrestrials *and* Cold War fever dreams—it needed only "some sex and the involvement of the Royal Family and the whole world would be paying attention," one journalist wrote. News articles described scientists rallying around Alvarez's theory in record time, especially after the so-called impacter camp delivered, in 1991, the geologic equivalent of DNA evidence: the "Crater of Doom," a 111-mile-wide cavity near the Mexican town of Chicxulub, on the Yucatán Peninsula. Researchers identified it as the spot where the fatal asteroid had punched the Earth. Textbooks and natural-history museums raced to add updates identifying the asteroid as the killer.

The impact theory provided an elegant solution to a prehistoric puzzle, and its steady march from hypothesis to fact offered a heartwarming story about the integrity of the scientific method. "This is nearly as close to a certainty as one can get in science," a planetary-science professor told *Time* magazine in an article on the crater's discovery. In the years since, impacters say they have come even closer to total certainty. "I would argue that the hypothesis has reached the level of the evolution hypothesis," says Sean Gulick, a research professor at the University of Texas at Austin who studies the Chicxulub crater. "We have it nailed down, the case is closed," Buck Sharpton, a geologist and scientist emeritus at the Lunar and Planetary Institute, has said.

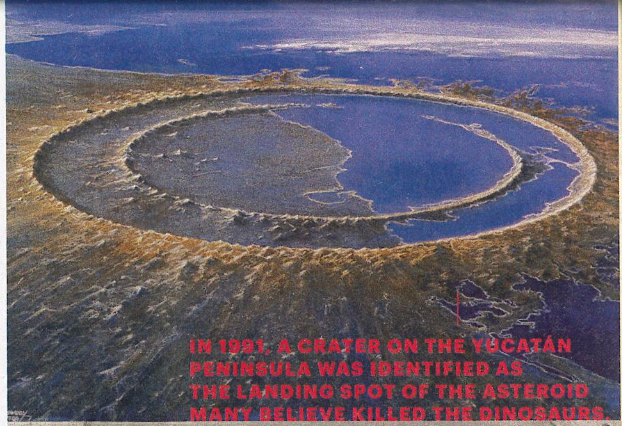
But Keller doesn't buy any of it. "It's like a fairy tale: 'Big rock from sky hits the dinosaurs, and boom they go.' And it has all the aspects of a really nice story," she said. "It's just not true."

While the majority of her peers embraced the Chicxulub asteroid as the cause of the extinction, Keller remained a maligned and, until recently, lonely voice contesting it. She argues that the mass extinction was caused not by a wrong-place-wrong-time asteroid collision but by a series of colossal volcanic eruptions in a part of western India known as the Deccan Traps—a theory that was first proposed in 1978 and then abandoned by all but a small number of scientists. Her research, undertaken with specialists around the world and featured in leading scientific journals, has forced other scientists to take a second look at their data. "Gerta uncovered many things through the years that just don't sit with the nice, simple impact story that Alvarez put together," Andrew Kerr, a geochemist at Cardiff University, told me. "She's made people think about a previously near-uniformly accepted model."

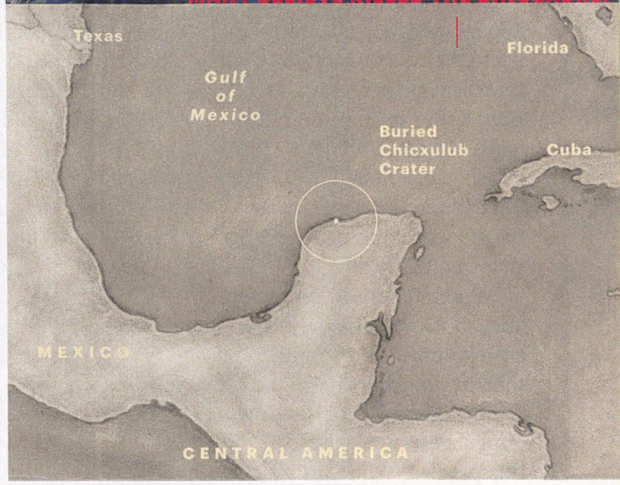
Keller's resistance has put her at the core of one of the most rancorous and longest-running controversies in science. "It's like the Thirty Years' War," says Kirk Johnson, the director of the Smithsonian's National Museum of Natural History. Impacters' case-closed confidence belies decades of vicious infighting, with the two sides trading accusations of slander, sabotage, threats, discrimination, spurious data, and attempts to torpedo careers. "I've never come across anything that's been so acrimonious," Kerr says. "I'm almost speechless because of it." Keller keeps a running list of insults that other scientists have hurled at her, either behind her back or to her face. She says she's been called a "bitch" and "the most dangerous woman in the world," who "should be stoned and burned at the stake."

Understanding the cause of the mass extinction is not an esoteric academic endeavor. Dinosaurs are what paleontologists call "charismatic megafauna": sexy, sympathetic beasts whose obliteration transfixes pretty much anyone with a pulse. The nature of their downfall, after 135 million years of good living, might offer clues for how we can prevent, or at least delay, our own end. "Without meaning to sound pessimistic," the geophysicist Vincent Courtillot writes in his book *Evolutionary Catastrophes*, "I believe the ancient catastrophes whose traces geologists are now exhuming are worthy of our attention, not just for the sake of our culture or our understanding of the zigzaggy path that led to the emergence of our own species, but quite practically to understand how to keep from becoming extinct ourselves."

This dispute illuminates the messy way that science progresses, and how this idealized process, ostensibly guided by objective reason and the search for truth, is shaped by ego, power, and politics. Keller has had to endure decades of ridicule to make scientists reconsider an idea they had confidently rejected. "Gerta had to fight very much to get into the position that she is in right now," says Wolfgang Stinnesbeck, a collaborator of Keller's from Heidelberg University. "It's thanks to her that the case is not closed."



IN 1991, A CRATER ON THE YUCATÁN PENINSULA WAS IDENTIFIED AS THE LANDING SPOT OF THE ASTEROID MANY BELIEVE KILLED THE DINOSAURS



DETLEV VAN RAVENSWAAY/SCIENCE SOURCE; DENISE NESTOR

2.

OVER THE COURSE

of its 4.5-billion-year existence, the Earth has occasionally lashed out against its inhabitants. At five different times, mass extinctions ensued.

Seven hundred million years ago, the oceans' single-cell organisms started linking together to form multicellular creatures. Four hundred and forty-four million years ago, nearly all of those animals were wiped out by the planet's first global annihilation. The Earth recovered—fish appeared in the seas, four-legged amphibians crawled onto land—and then, 372 million years ago, another catastrophe destroyed three-quarters of all life. For more than 100 million years after *that*, creatures thrived. The planet hosted the first reptiles, the first shelled eggs, the first plants with seeds. Forests swarmed with giant dragonflies whose wings stretched two feet across, and crawled with millipedes nearly the length of a car. Then, 252 million years ago, the "Great Dying" began. When it finished, 96 percent of all species had vanished. The survivors went forth and multiplied—until, 201 million years ago, another mass extinction knocked out half of them.

The age of the dinosaurs opened with continents on the move. Landmasses that had spent millions of years knotted together into the supercontinent of Pangaea began to drift apart, and oceans—teeming with sponges, sharks, snails, corals, and crocodiles—flooded into the space between them. It was swimsuit weather most places on land: Even as far north as the 45th parallel, which today roughly marks the U.S.–Canada border, the climate had a humid, subtropical feel. The North Pole, too warm for ice, grew lush with pines, ferns, and palm-type plants. The stegosaurs roamed, then died, and tyrannosaurs took their place. (More time separates stegosaurs from tyrannosaurs—about 67 million years—than tyrannosaurs from humans, which have about 66 million years between them.) It was an era of evolutionary innovation that yielded the first flowering plants, the earliest placental mammals, and the largest land animals that ever lived. Life was good—right up until it wasn't.

That's according to the Alvarez theory, which mass-extinction devotees, with their typical gallows humor, refer to as the "bad weekend" scenario: The dinosaurs didn't see the end coming, didn't stand a chance, and by Monday it was all, abruptly, over. *Big rock from sky hits the dinosaurs, and boom they go.* (Some of the species that avoided the dinosaurs' fate are still around today in a form nearly identical to their ancestors, including gingko trees, magnolias, roaches, crocodiles, and tortoises, which Keller keeps as pets.)

Alvarez's theory was a boon for the catastrophist school of thought, which maintains that the Earth is shaped by sudden, violent events—and can turn on its occupants in a heartbeat. The impacters contend that the fossils of both marine- and land-dwelling organisms show an abrupt and instantaneous die-off at virtually the same moment, geologically speaking, that the asteroid hit. "If you look at the extinction rate up to the event and you look at the recovery after, this is the most sudden of all the known extinctions," Sean Gulick says. "This one is like a knife-sharp boundary in the geologic record"—consistent with the kind of destruction an asteroid could cause.

Alvarez's theory initially faced strong opposition from the gradualists, who argue that enormous planetary changes tend to result from slower, less adrenaline-pumping forces. Among those who disagreed with him was Keller.

Her first interaction with the community investigating the dinosaurs' disappearance took place at a 1988 conference on global catastrophes. She presented results from her three-year analysis of a rock section in El Kef, Tunisia, that has long been considered one of the most accurate records of the extinction. Keller specializes in studying the fossils of single-celled marine organisms called foraminifera—"forams," once you're on a nickname basis, as Keller is. (She considers these creatures, which include many species of plankton, "old friends.") Because their fossils are plentiful and well preserved, paleontologists can trace their extinction patterns with considerable accuracy, and thus frequently rely on them as a proxy for other creatures' well-being.

When Keller examined the El Kef samples, she did not see a "bad weekend," but a bad era: Three hundred thousand years before Alvarez's asteroid struck, some foram populations had already started to decline. Keller found that they had become less and less robust until, very rapidly, about a third of them vanished. "My takeaway was that you could not have a single instantaneous event causing this pattern," she told me. "That was my message at that meeting, and it caused an enormous turmoil." Keller said she barely got through her introduction before members of the audience tore into her: "Stupid." "You don't know what you're doing." "Totally wrong." "Nonsense."

Keller barely got through her introduction before the audience tore into her: "Stupid." "You don't know what you're doing." "Totally wrong." "Nonsense."

Ad hominem attacks had by then long characterized the mass-extinction controversy, which came to be known as the "dinosaur wars." Alvarez had set the tone. His numerous scientific exploits—winning the Nobel Prize in Physics, flying alongside the crew that bombed Hiroshima, "X-raying" Egypt's pyramids in search of secret chambers—had earned him renown far beyond academia, and he had wielded his star power to mock, malign, and discredit opponents who dared to contradict him. In *The New York Times*, Alvarez branded one skeptic "not a very good scientist," chided dissenters for "publishing scientific nonsense," suggested ignoring another scientist's work because of his "general incompetence," and wrote off the entire discipline of paleontology when specialists protested that the fossil record contradicted his theory. "I don't like to say bad things about paleontologists, but they're really not very good scientists," Alvarez told *The Times*. "They're more like stamp collectors."

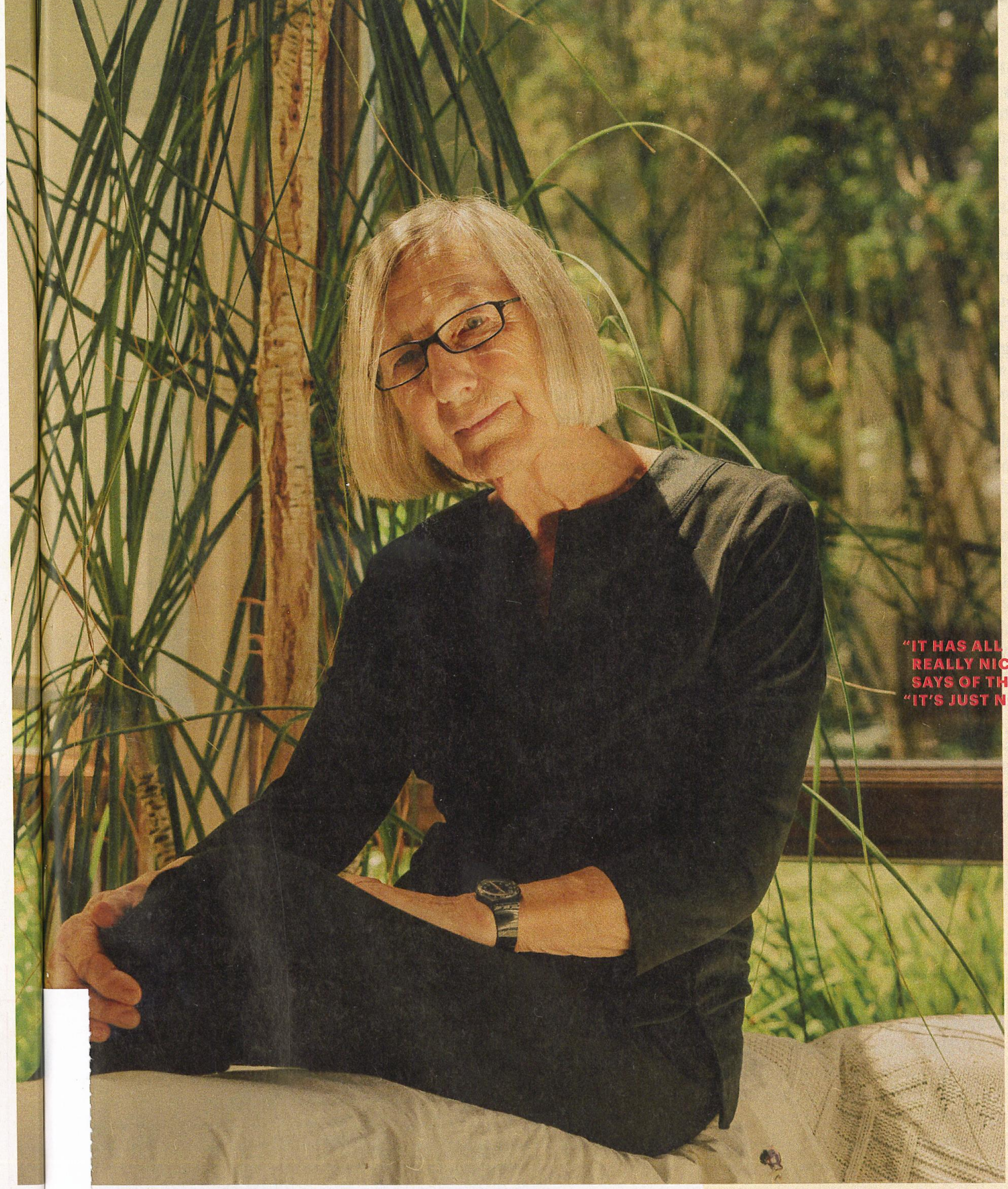
Scientists who dissented from the asteroid hypothesis feared for their careers. Dewey McLean, a geologist at Virginia Tech credited with first proposing the theory of Deccan volcanism, accused Alvarez of trying to block his promotion to full professor by bad-mouthing him to university officials. Alvarez denied doing so—while effectively bad-mouthing McLean to university officials. "If the president of the college had asked me what I thought about Dewey McLean, I'd say he's a weak sister," Alvarez told *The Times*. "I thought he'd been knocked out of the ball game and had just disappeared, because nobody invites him to conferences anymore." Chuck Officer, another volcanism proponent, whom Alvarez dismissed as a laughingstock, charged that *Science*, a top academic journal, had become biased. The journal reportedly published 45 pieces favorable to the impact theory during a 12-year period—but only four on other hypotheses. (The editor denied any favoritism.)

That the dinosaur wars drew in scientists from multiple disciplines only added to the bad blood. Paleontologists resented arriviste physicists, like Alvarez, for ignoring their data; physicists figured the stamp collectors were just bitter because they hadn't cracked the mystery themselves. Differing methods and standards of proof failed to translate across fields. Where the physicists trusted models, for example, geologists demanded observations from fieldwork. Yet even specialists from complementary disciplines like geology and paleontology butted heads over crucial interpretations: They consistently reached opposing conclusions as to whether the disappearance of the species was fast (consistent with an asteroid's sudden devastation) or slow (reflecting a more gradual cause). In 1997, hoping to reconcile disagreement over the speed of extinction, scientists organized a blind test in which they distributed fossil samples from the same site to six researchers. The researchers came back exactly split.

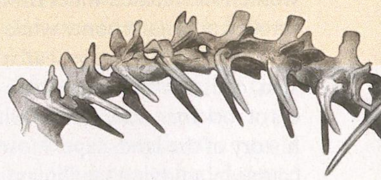
Keller and others accuse the impacters of trying to squash deliberation before alternate ideas can get a fair hearing. Though geologists had bickered for 60 years before reaching a consensus on continental drift, Alvarez declared the extinction debate over and done within two years. "That the asteroid hit, and that the impact triggered the extinction of much of the life of the sea ... are no longer debatable points," he said in a 1982 lecture. "Nearly everybody now believes them." After Alvarez's death, in 1988, his acolytes took up the fight—most notably his son and collaborator, Walter, and a Dutch geologist named Jan Smit, whom Keller calls a "crazy SOB."

Ground down by acrimony, many critics of the asteroid hypothesis withdrew—including Officer and McLean, two of the most outspoken opponents. Lamenting the rancor as "embarrassing to geology," Officer announced in 1994 that he would quit mass-extinction research. Though he did ultimately get promoted, McLean later wrote on his faculty website that Alvarez's "vicious politics" had caused him to develop serious health problems and that, for fear of a relapse, he couldn't research Deccan volcanism without "the greatest of difficulty." "I never recovered physically or psychologically from that ordeal," he added. Younger scientists avoided the topic, fearing that they might jeopardize their careers. The impact theory solidified, and volcanism was largely abandoned.

But not by everyone. "Normally, when people get attacked and given a hard time, they leave the field," Keller told me. "For me, it's just the opposite. The more people attack me, the more I want to find out what's the real story behind it."



"IT HAS ALL THE ASPECTS OF A REALLY NICE STORY," KELLER SAYS OF THE ASTEROID THEORY. "IT'S JUST NOT TRUE."



PHOTOGRAPHS BY COLE WILSON

As Keller has steadily accumulated evidence to undermine the asteroid hypothesis, the animosity between her and the impacters has only intensified. Her critics have no qualms about attacking her in the press: Various scientists told me, on the record, that they consider her "fringe," "unethical," "particularly dishonest," and "a gadfly." Keller, not to be outdone, called one impacter a "crybaby," another a "bully," and a third "the Trump of science." Put them in a room together, and "it may be World War III," Andrew Kerr says.

As the five-hour drive to our hotel in rural India turned into 12 after a stop to gather rock samples, Keller aired a long list of grievances. She said impacters had warned some of her collaborators not to work with her, even contacting their supervisors in order to pressure them to sever ties. (Thierry Adatte and Wolfgang Stinnesbeck, who have worked with Keller for years, confirmed this.) Keller listed numerous research papers whose early drafts had been rejected, she felt, because pro-impact peer reviewers "just come out and regurgitate their hatred." She suspected repeated attempts to deny her access to valuable samples extracted from the Chicxulub crater, such as in 2002, when the journal *Nature* reported on accusations that Jan Smit had seized control of a crucial piece of rock—drilled at great expense—and purposefully delayed its distribution to other scientists, a claim Smit called "ridiculous." (Keller told me the sample went missing and was eventually found in Smit's duffel bag; Smit says this is "pure fantasy.") Several of Keller's stories—about a past adviser, for example, or a former postdoc—ended with variations of the same punch line: "He became my lifelong enemy."

3. KELLER PLANNED TO

spend a week gathering rocks in two different regions of India, beginning with the area around Basar, a dusty village of 5,800 in the center of the country. Our days in the field settled into a predictable routine. From about 7:30 every morning until as late as midnight, we fanned out from the hotel. Our six- or seven-hour drives to distant quarries revealed the rhythms of rural neighborhoods, where women still fetched water from communal pumps and shepherds scrolled on smartphones while grazing their flocks.

The geologists were searching for outcrops—areas where erosion, construction, or tectonic activity had exposed the inner layers of rock formations, from which the scientists could decode the history of the landscape. Most mornings, Thierry Adatte set our course by studying satellite images for signs of quarries (big beige rectangles) or switchback roads (pale zigzags). Keller and her colleagues saw the landscape in greater relief than most: When explaining how volcanoes extrude magma from the planet's inner mantle, Mike Eddy characterized the surface of the Earth—the foundation of our homes, cities, civilizations—as "this little tiny scum," as puny as the skin of milk that gathered on our tea each morning.

For someone accustomed to thinking about time in multimillion-year increments, Keller grew surprisingly impatient over wasted minutes. "Why so slow?" she muttered next to me in the back seat, craning her neck to see the speedometer as we plowed into oncoming traffic and past slower cars. "Should I go and push?" She discouraged us from stopping at roadside stands for tea and, over meals, needled her colleagues about their halting progress on several co-authored manuscripts.

Keller's publication list runs to more than 250 articles, about half of which attempt to poke holes in the impact theory. After her 1988 paper on forams in Tunisia, she decided to see whether the slow and steady extinction pattern she'd observed at El Kef held true elsewhere, and she analyzed foram populations pre- and post-Chicxulub at nearly 300 sites around the world. Over and over, Keller saw "no evidence of a sudden mass killing." Instead, she found more proof that the Earth's fauna grew progressively more distressed starting 300,000 years before the extinction. The forams, for example, gradually shrank, declined in number, and showed less diversity, until only a handful of species remained—results consistent with what many paleontologists have observed for animals on land during the same time.

More problematic still, Chicxulub did not appear to Keller to have been particularly deadly. Samples she gathered in El Peñón, Mexico, west of the crater, revealed healthy populations of forams even after the asteroid struck. Photosynthetic creatures, which should have been doomed by the dust cloud's shroud of darkness, also managed to survive.

And then there was the issue of the four previous mass extinctions. None appeared to have been triggered by an impact, although numerous other asteroids have pummeled our planet over the millennia. (Pro-impact scientists counter that not only was the Chicxulub asteroid gigantic, it also landed in the deadliest possible site: in shallow waters, where it kicked up climate-altering vaporized rock.)

Keller found the asteroid's timing suspect, too. The impacters had long pegged Chicxulub's age to the date of the extinction, which is widely agreed to have occurred approximately 66 million years ago. They reasoned that the two must be synchronous, because the destruction caused by the asteroid would have been near-instantaneous. This looked like circular logic to Keller, who in 2002 set out to investigate whether the two really were concurrent. Analyzing samples drilled from deep within the Chicxulub crater, Keller uncovered 20 inches of limestone and other sediment between the fallout from the asteroid and the forams' most pronounced die-off. This was evidence that thousands of years had elapsed in between, she argued. (Smit's findings from the same samples were diametrically opposed; he countered that a tsunami, triggered by the asteroid, had deposited the sediment essentially overnight.) Based on similar results from Haiti, Texas, and elsewhere in Mexico, Keller concluded that the asteroid had hit 200,000 years before the extinction—far too early to have caused it.

So what *did* cause it? Keller began searching for other possible culprits. She was looking for a menace that had become gradually more deadly over hundreds of thousands of years, such that it would have caused increasing stress followed by a final, dramatic obliteration.

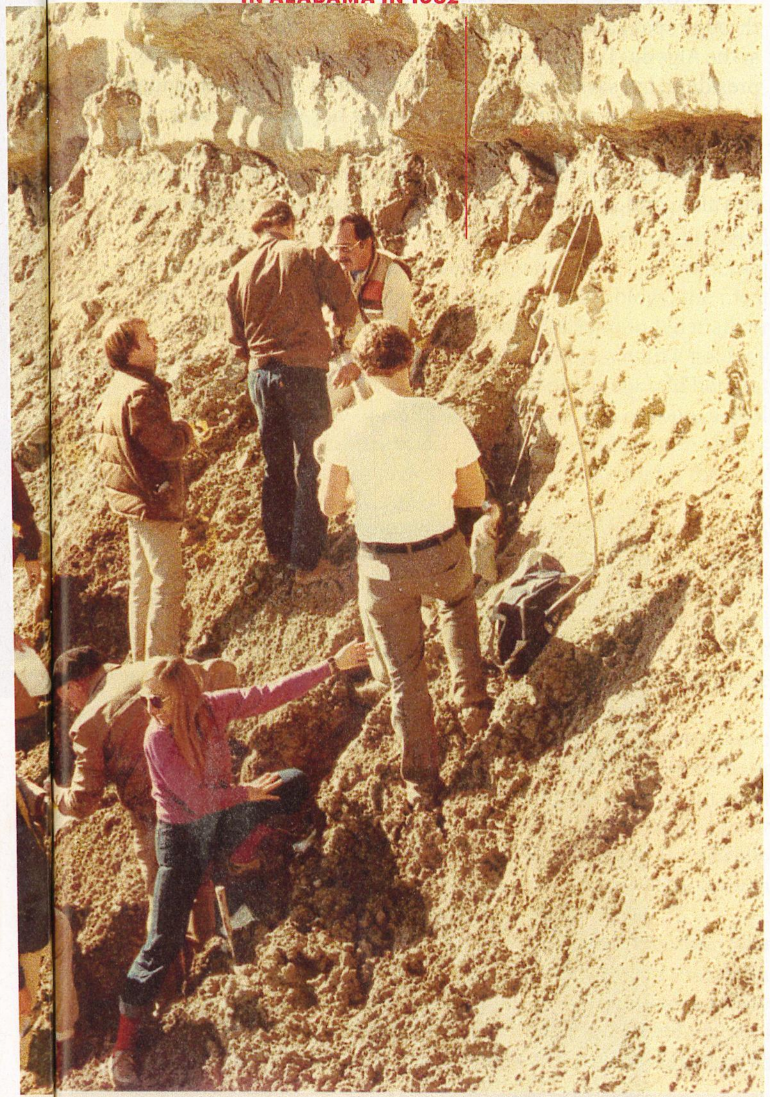
She had a promising lead: The Earth's four prior mass extinctions are each associated with enormous volcanic eruptions that lasted about 1 million years apiece. The fifth extinction, the one that doomed the dinosaurs, occurred just as one of the largest volcanoes in history seethed in the Deccan Traps.

Yet it is not only a volcano's absolute size that makes it catastrophic, but also the pace of its eruptions. The Earth can recover from large environmental disturbances—unless those disruptions come too quickly, compounding the injury until they overwhelm the planet's ability to equilibrate.

Until the mid-1980s, geologists believed that Deccan's network of volcanoes had erupted over millions of years, simmering so gently as to be mostly harmless. A 1986 paper concluded that the bulk of its eruptions had occurred within 1 million years, but scientists still couldn't connect those explosions to the mass dying. Keller's first paper on Deccan volcanism, in 2008, provided unprecedented evidence that suggested there could be a link: She documented huge lava flows just preceding the extinction, which was demarcated in the rock record by the fossils of creatures that had evolved only after the mass dying. Using new dating techniques, Keller and her Princeton colleagues further condensed Deccan's activity to about 750,000 years. Now, on this trip, she was drafting a new paper showing that the biggest Deccan eruptions—accounting for nearly half of the volcanoes' explosive output—had been squeezed into the last 60,000 years before the mass extinction. During that time, so much gas, ash, and lava were pumped into the ecosystem that the Earth hit "the point of no return," she said.

GERTA KELLER

KELLER DOING FIELDWORK IN ALABAMA IN 1982



On this excursion, Keller hoped to gather samples that would allow her to create a detailed timeline of Deccan activity in the 100,000 years leading up to the extinction. The goal: to see whether its biggest belches correlated with environmental stress and mass dying around the world. Basar was 300 miles east of some of the highest points in the Deccan Traps, an area near the epicenter of the eruptions. Keller had chosen Basar because she suspected that the long, low stretches of basalt around us had been formed by some of the largest lava flows—ejected during major eruptions immediately preceding the extinction. To prove that, however, Keller needed to have the rock dated.

We were snaking down a sinewy road one afternoon when Adatte hollered, the van screeched to a stop, and everyone scrambled out to inspect a steep hill in the elbow of a hairpin turn. It didn't look like much to me. Rising up from the asphalt were several yards of pebbly, khaki-colored rock, then a thin band of seafoam-green rock, followed by a pinkish layer, and then round, brown rocks interspersed with white roots.

Adatte sank to his knees and burrowed into the pebbles. Eddy licked a rock, to determine whether it was clay. Keller sprinted up the incline until she was eye level with the greenish layer.

"Keep digging!" Keller told Adatte. "This is a real bonanza for us!"

She translated the outcrop for me as though it were text in a foreign language. Rocks record the passage of time vertically: The distance between where Adatte sat covered in gravel and where Keller perched at the top of the hill potentially represented the progression of several hundred thousand years. "Think of it as walking up through time," Keller said. She passed me a chunk of the seafoam-colored rock and pointed to a tiny white fossil protruding like a baby tooth: evidence of tempestites, broken shells carried in by a storm. The area near Keller's head had evidently once been a prehistoric lake or seaway. The pinkish soil above *that* had been buried under lava—the brown rocks covered with tangled roots. Since the pinkish layer and the shells predated the flows, they could help pinpoint that particular eruption.

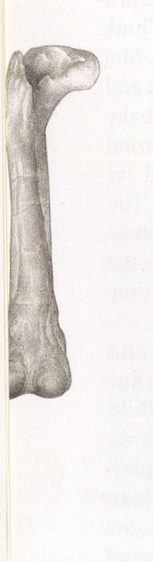
Geology is a field of delayed gratification, and there was little else the scientists could say definitively before getting the samples into a lab. While Syed Khadri fielded questions from puzzled locals who wanted to know why the foreigners were playing in the dirt, Keller, Adatte, and Eddy filled clear-plastic bags with fistfuls of rock to ship home.

Back in the van, Adatte told me about a recent conference where several researchers had debated the validity of Deccan volcanism versus the impact theory in front of an audience of their peers, who had then voted, by a show of hands, on which they thought had caused the extinction. Adatte said the result was 70–30 in favor of volcanism. I heard later from the paleontologist Paul Wignall, who'd argued for the impact side, that Chicxulub had won 60–40, though he conceded that the scientists were essentially split—clearly, the question was far from resolved. When I asked Wignall who had rescued Deccan volcanism and helped popularize it, he said, "If you were to name one person, you would name Gerta."

4.

OUR LONG STRETCHES in the car provided Keller ample time to continue inventorying her own numerous brushes with extinction.

Her childhood could pass for the opening of a Brothers Grimm fairy tale. Keller's mother was the eldest of 12 children in a wealthy Lichtenstein family. According to stories Keller heard as a kid, their fortune from hotels and real estate kept the children wearing Parisian couture and summering in Austria. But the old-money clan grew distant from Keller's mother after she married Keller's father, one of 18 children born to Swiss woodworkers, whose dreams of becoming a farmer clashed with the bride's privileged upbringing. The young couple took out loans to buy a farm, where they raised cows, sheep, ducks, rabbits, vegetables, and their 12 children, the sixth of whom was Keller.



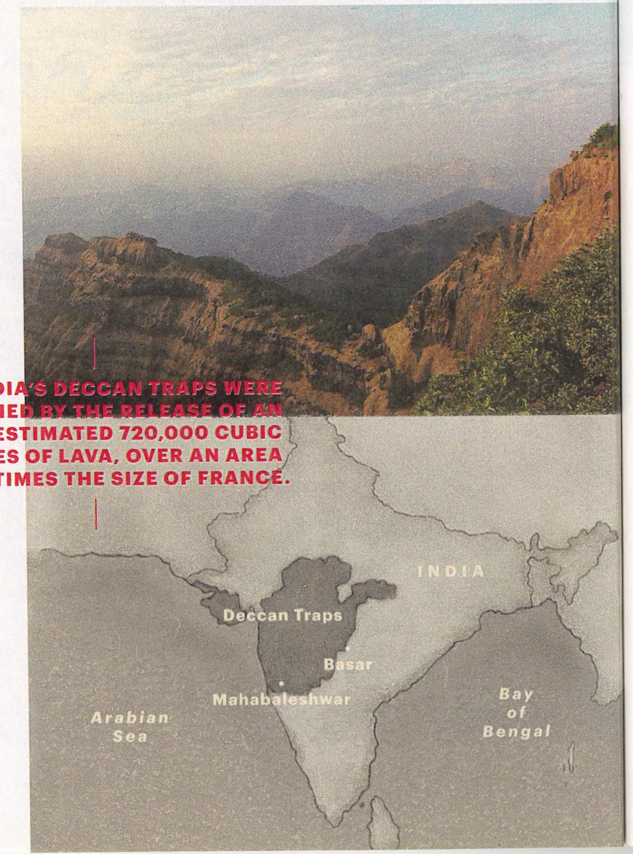
Keller grew up among rocks, in the alpine crevices of a Swiss village where the neighbors still believed in witches. Although Keller's father enlisted his brood to tend the land—working them so hard that a neighbor once reported him—the family constantly teetered on the brink of bankruptcy. To put meat on the table, Keller's mother once stewed up one of the cats the family kept on the farm. Another time, she gave an older daughter some fresh "mutton" as a gift—in actuality, Keller's butchered pet dog.

Keller attended a local public school where one teacher oversaw four grades, an arrangement Keller enjoyed because it allowed her to tackle the older students' more difficult assignments. Then, much as now, she considered herself in a league apart from her peers. "I didn't socialize much with the other kids, because I thought they were too dumb," Keller told me. ("In school, well, how should I put this? I was very good at whatever I did," she said another time.) She devoured books, completed her siblings' homework in exchange for them doing her chores, and fumed that girls had to cook and clean while boys got to study science and math.

At age 12, Keller wanted to become a doctor. Her teacher, concerned by these delusions of grandeur, called in a Jungian psychologist to administer a Rorschach test and remind Keller that the daughter of such a poor family should aspire to less. Shortly afterward, Keller received a visit from a priest: Keller's mother wanted him to take her to a nunnery, but Keller refused to go. Two years later, Keller—given the choice of becoming a maid, a salesgirl, or a seamstress—apprenticed with a dressmaker. Her mother hoped that she would help clothe her siblings. Keller eventually worked for Christian Dior's fashion house, sewing gowns for 25 cents an hour.

In her teens, Keller resolved to die before she turned 23. She was suicidal for reasons she declined to explain to me in detail, but attributed generally to frustration with Swiss society—her sense that "options were limited for a kid from a poor family," plus "the sexual harassment" and "the way women were treated." "You were just a piece of meat at any time," she told me. She tried to kill herself by taking sleeping pills, failed, then figured she would live as dangerously as possible and die in the process. "I just never got killed," she said. "Not completely, anyway."

In 1964, at age 19, Keller quit her job in Zurich and hitchhiked through Spain and North Africa for six months. She was detained at the Algeria–Tunisia border amid a coup that deposed Algeria's president, but says she eventually charmed an army commander into letting her pass and even providing her with an escort—a drug trafficker who happened to be heading the same way. She continued her trek around the globe: Greece, Israel, Czechoslovakia, and Austria, where her plan to continue on to Russia



INDIA'S DECCAN TRAPS WERE FORMED BY THE RELEASE OF AN ESTIMATED 720,000 CUBIC MILES OF LAVA, OVER AN AREA THREE TIMES THE SIZE OF FRANCE.

BIANCA BOSKER; DENISE NESTOR

was interrupted when her health failed. It was hepatitis, which she had contracted at the Algerian border. "At the hospital, they didn't think that I would live," she said.

After a year of recovery, Keller set sail from Genoa to Australia, which she planned to use as a jumping-off point for travel throughout Asia. Keller recalls that during the three-week journey, her ship collided with its sister vessel, hit a typhoon in the Indian Ocean, and was found to be infested with mafiosi smuggling weapons. When Keller disembarked, an Australian official tried to steer her to a sweatshop crammed with immigrants at sewing machines, attempting to negotiate a cut of Keller's pay, in perpetuity. But Keller spoke better English than the official realized. She discovered the plan, threatened to report the official, and worked instead as a nurse's aide, then a waitress.

She was returning from a picnic near Sydney's Suicide Cliffs one day when a bank robber, fleeing the scene of the crime, shot her, puncturing her lungs, shattering her ribs, and landing her in intensive care. "Woman Shot 'for No Reason,'" announced a headline in *The Sydney Morning Herald*. ("She looked dead," a witness told the paper.) A priest came to administer last rites and, as Keller hovered in and out of consciousness, commanded her to confess her sins. Twice, she refused. "I credit that priest with my survival, because he made me so mad," Keller told me. The experience also cured her of her death wish.

Keller eventually made her way to Asia, then arrived in California with plans to continue to South America. Instead, she settled in San Francisco and, at age 24, returned to school. She enrolled in community college, telling the registrar that her academic records had been destroyed in a fire, and later transferred to San Francisco State University, where she majored in anthropology, the most scientific field she could enter without a background in math or science. Her passion for mass extinction began with a geology class she took during her junior year. The professor told her that if she liked rocks and enjoyed travel, she should become a geologist—"because there are rocks everywhere, and you can always dream up some project to do and someone will fund it for you," Keller recalled him saying.

She became the first member of her family to graduate from college, and then one of the first women to receive a doctoral degree in earth sciences from Stanford. In 1984, she joined the faculty at Princeton, where she is currently one of two tenured women in the geosciences department. (According to a 2017 survey by the American Geosciences Institute, 85 percent of the country's tenured geosciences professors are male.)

Although Keller is alert to situations in which women are treated differently from men, she hesitates to blame sexism for the hostility she has faced. "There is clearly sexism going on at some level, but there is no way I would be able to prove it, nor would I want to," she told me. "Because to me, it is critically important that I, as a woman, can make it in science without even referring to sexism."

But Vincent Courtillot, an early proponent of Deccan volcanism who has closely followed Keller's work, thinks that prejudice has tainted other scientists' treatment of her. "She is a forceful woman and she is a courageous woman in a world where, I don't have to tell you, for someone to rise to the top of geology as a female is much harder than for a male," he says.

Keller adores her work. Never before have I encountered someone so gleeful about catastrophe. When we discussed the risk that the Yellowstone supervolcano might blow at any time, Keller's eyes twinkled. "It's a fun idea," she said. To her, mass extinctions are not depressing. Rather, they illuminate life's fundamental questions. "Ask yourself, 'Where did you come from?' 'Why are we here?'" Keller told me. "If you extract all the religious bullshit away from it, you have to go to nature. And the only way to find out is really to study the history."

Though Keller's critics accuse her of being ego-driven and publicity-hungry, in the time I spent with her she showed little concern for her legacy. Instead, she expressed a dim view of what 44,000 years of human civilization will leave behind, much less her own few decades on the planet. "Just think, if we wipe ourselves out in the next couple of thousand years, there will be no record left," she said, studying the eroded remains of 66-million-year-old basalt as we drove back to the Hyderabad airport, from which we would travel to the heart of the Deccan Traps. "I mean, it's a second. A nanosecond in history. Who will find our remains?"

5.

ON JUNE 8, 1783, Iceland's Laki volcano began to smoke. The ground wrenched open "like an animal tearing apart its prey" and out spilled a "flood of fire," according to an eyewitness's diary. Laki let loose clouds of sulfur, fluorine, and hydrofluoric acid, blanketing Europe with the stench of rotten eggs. The sun disappeared behind a haze so thick that at noon it was too dark to read. (Unlike the cone-shaped stratovolcanoes from third-grade science class, both Deccan and Laki were fissure eruptions, which fracture the Earth's crust, spewing lava as the ground pulls apart.)

Destruction was immediate. Acid rain burned through leaves, blistered unprotected skin, and poisoned plants. People and animals developed deformed joints, softened bones, cracked gums, and strange growths on their bodies—all symptoms of fluorine poisoning. Mass death began eight days after the eruption. More than 60 percent of Iceland's livestock died within a year, along with more than 20 percent of its human population. And the misery spread. Benjamin Franklin reported a "constant fog" over "a great part of North America." Severe droughts plagued India, China, and Egypt. Cold temperatures in Japan ushered in what is remembered as the "year without a summer," and the nation suffered the worst famine in its history. Throughout Europe, crops turned white and withered, and in June, desiccated leaves covered the ground as though it were October. Europe's famine lasted three years; historians have blamed Laki for the start of the French Revolution.

"But that's just a short-term event from a relatively minor eruption, compared with Deccan," Keller told me. A single Deccan eruption was "thousands of times larger" than Laki, she said. "And then you repeat that over and over again. For basically 350,000 years before the massive die-off."

Laki released 3.3 cubic miles of lava; Deccan unleashed an estimated 720,000 cubic miles, eventually covering an area three times the size of France. It took us five hours of driving, an hour-and-a-half flight from Hyderabad to Pune, and another three hours in the car to trace the lava flows from some of their farthest, flattest reaches back to some of their highest points, in Mahabaleshwar, a vertiginous town crowded with honeymooners. Mountains of basalt 2.1 miles high—nearly twice as tall as the Grand Canyon is deep—extended as far as I could see. Even the geologists, who had visited the Deccan Traps multiple times before, gaped at the landscape.

"It's mind-blowing," Eddy said. "Every time."

Keller, whose food poisoning had gone from bad to worse, made the van pull over so we could revisit an outcrop she'd sampled twice before, on previous trips. At the base of an undulating wall of black basalt, Keller ran her hand over a blood-colored layer of rock, bumpy and inflamed as a scab. Where we now stood was virtually within a blink of an eye of the mass extinction, she explained: Keller's collaborators had dated this red layer and found that it was deposited tens of thousands of years before the extinction, just before Deccan's largest and most lethal eruptions began.

"Shit hits the fan for the last 40,000 years," Keller said. "The eruptions *really* took off. Huge. Absolutely huge. That's when we have the longest lava flows on Earth, into the Bay of Bengal"—more than 600 miles away, practically the length of California.

A drawing that hangs over Keller's desk at Princeton depicts her vision of this apocalypse, which was heavily informed by accounts of how Laki poisoned Iceland's livestock. "I told [the artist], 'Yellow foaming at the mouth!' " Keller recounted, delighted. In the illustration, dinosaurs, gurgling lime-green vomit, writhe on a hill spotted with flames and charred tree stumps; just behind them, a diagonal gash in the ground blazes with lava and spews dark, swirling clouds. According to Keller's research, while Deccan's lava flows would have devastated the Indian subcontinent, its release of ash, toxic elements (mercury, lead), and gases (sulfur, methane, fluorine, chlorine, carbon dioxide) would also have blown around the world, wreaking havoc globally.

As she sees it, the ash, mercury, and lead would have settled over habitats, poisoning creatures and their food supply. The belches of sulfur would have initially cooled the climate, then they would have drenched the Earth in acid rain, ravaging the oceans and destroying vegetation that land animals needed to survive. The combination of carbon dioxide and methane would have eventually raised temperatures on land by as much as 46 degrees Fahrenheit, further acidifying oceans and making them inhospitable to plankton and other forams. Once these microscopic creatures disappear from the base of the food chain, larger marine animals follow. "At that point, extinction is inevitable," Keller said.

Rocks elsewhere in the world support the sequence of events Keller has discerned in the Deccan Traps. She and her collaborators have found evidence of climate change and skyrocketing mercury levels following the largest eruptions, and other researchers have documented elevated concentrations of sulfur and chlorine consistent with severe pollution by volcanic gases. Keller posits that even the iridium layers could be linked to Deccan's eruptions, given that volcanic dust can carry high concentrations of the element.

She also sees Deccan's fingerprints in the fossil record. The gradual decline of the forams—followed by their sudden, dramatic downfall—aligns with Deccan's pattern of eruptions: Over several hundred thousand years, its volcanic activity stressed the environment, until its largest emissions dealt a final, devastating blow. The Earth's flora and fauna did not show signs of recovery for more than 500,000 years afterward—a time period that coincides with Deccan's ongoing belches. The volcano simmered long after most species had vanished, keeping the planet nearly uninhabitable.

6.

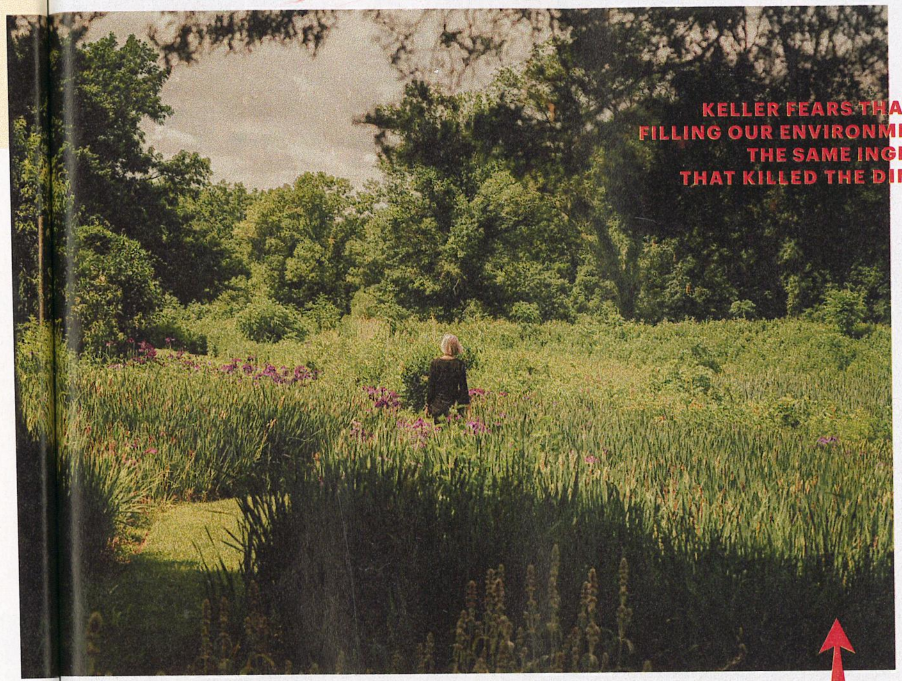
"HER CONCLUSIONS ARE way off," Jan Smit, the Dutch scientist, told me. After nearly 40 years of arguing, the two sides still cannot agree on fundamental facts. Smit and other impacters counter Keller's scenario with a long list of rebuttals: The planet's species went extinct "almost overnight," Smit insists, too quickly to be caused by Deccan volcanism. India's volcanoes hiccuped for hundreds of thousands of years, too weakly and for too long to be deadly, Keller's critics contend. They argue that there is no evidence that species suffered while Deccan simmered, and that the biggest volcanic eruptions occurred after the extinction, too late to have been the catalyst. Besides, they add, new dating places the asteroid's impact within 32,000 years of the annihilation—as close as a "gnat's eyebrow," says the geochronologist Paul Renne, who led the study.

Some scientists have attempted to find a middle ground between the two camps. A team at UC Berkeley, headed by Renne, has recently incorporated volcanism into the asteroid theory, proposing that Chicxulub's collision unleashed earthquakes that in turn triggered Deccan's most destructive pulses. But Keller rejects this hypothesis. "It's impossible," she told me. "They are trying to save the impact theory by modifying it."

The greatest area of consensus between the volcanists and the impacters seems to be on what insults to sling. Both sides accuse the other of ignoring data. Keller says that her pro-impact colleagues "will not listen or discuss evidence that is contrary to what they believe"; Alan Hildebrand, a prominent impacter, says Keller "doesn't look at all the evidence." Each side dismisses the other as unscientific: "It's not science. It sometimes seems to border on religious fervor, basically," says Keller, whose work Smit calls "barely scientific." Both sides contend that the other is so stubborn, the debate will be resolved only when the opposition croaks. "You don't convince the old people about a new idea. You wait for them to die," jokes Courtillot, the volcanism advocate, paraphrasing Max Planck. Smit agrees: "You just have to let them get extinct."

All the squabbling raises a question: How will the public know when scientists have determined which scenario is right? It is tempting, but unreliable, to trust what appears to be the majority opinion. Forty-one co-authors signed on to a 2010 *Science* paper asserting that Chicxulub was, after all the evidence had been evaluated, conclusively to blame for the dinosaurs' death. Case closed, *again*. Although some might consider this proof of consensus, dozens of geologists, paleontologists, and biologists wrote in to the journal contesting the paper's methods and conclusions. Science is not done by vote.

Ultimately, consensus may be the wrong goal. Adrian Currie, a philosopher of science at Cambridge University, worries that the feverish competition in academia coupled with the need to curry favor with colleagues—in order to get published, get tenure, or get grant money—rewards timid research at the expense of maverick undertakings. He and others argue that controversy produces progress, pushing experts to take on more sophisticated questions. Some of Keller's most outspoken critics told me that her naysaying has motivated their research. "She keeps us sharp, definitely," Smit said. Though trading insults is not the mark of dispassionate scientific research, perhaps detached investigation is not ideal, either. It is passion, after all, that drives scientists to dig deeper, defy the majority, and hunt rocks in rural India for 12 hours at a stretch while suffering acute gastrointestinal distress.



KELLER FEARS THAT WE ARE FILLING OUR ENVIRONMENT WITH THE SAME INGREDIENTS THAT KILLED THE DINOSAURS.

COLE WILSON

7.

KELLER'S ATTENTIVENESS TO the stories that rocks tell enables her to live concurrently in the past, present, and future. She was here, driving through Pune's smog-filled mountains. The sight of their jagged outlines simultaneously transported her back in time 66 million years, to when the Indian subcontinent split apart, spewing gas, ash, and fire. That, in turn, evoked the eventual demise of the human species, which Keller argues will be triggered by forces similar to Deccan volcanism.

Keller fears that we are filling our environment with the same ingredients—sulfur, carbon dioxide, mercury, and more—that killed the dinosaurs and that, left unchecked, will catalyze another mass extinction, this one of our own devising. "You just replace Deccan volcanism's effect with today's fossil-fuel burning," she told me. "It's exactly the same."

Keller sees a bleak future when she looks at our present. Oceans are acidifying. The climate is warming. Mercury levels are rising. Countless species are endangered and staring down extinction—much like the gradual, then rapid, downfall of the forams. Whether or not Deccan ultimately caused the mass extinction, its eruptions illuminate how our current environment may react to man-made pollutants. If Deccan *was* responsible, however, Keller's theory casts our current actions in a terrifying light. (Not to be outdone, impacters recently highlighted the Chicxulub asteroid's relevance to the present day in a paper for *Science*, arguing that the asteroid injected enough carbon dioxide into the atmosphere to cause 100,000 years of global warming.)

The asteroid theory has ingrained in the public's imagination the idea that mass extinction will be quick and sensational—that we will go out in a great, momentous ball of fire. *Big rock from sky hits the humans, and boom they go.* But Keller's vision of the sixth extinction, given what she sees as its parallels with Deccan volcanism, suggests that the end will be drawn out and difficult to recognize as such within humans' brief conception of time. "We are living in the middle of a mass extinction today," Keller told me. "But none of us feel that urgency, or that it really is so."

Death felt especially present the afternoon we visited a quarry that stretched 15 miles through the countryside. The landscape was eviscerated. A mountain in the distance had been cut away, leaving a rectangular, unnatural pit. Hills streaked with orange, purple, red, and yellow dirt rose around us, their peaks active with trucks dumping more rainbows of dirt. It was spoil, Eddy explained, the unwanted earth that the strip miners had to dig through to reach the Jurassic seam—the coal that, 145 million years ago, was a swamp.

The scene got Keller thinking about mass extinctions still to come and the geologists of the future ("They'll probably be cockroaches"), who, while studying this landscape, will be hopelessly confused by all these rock layers jostled on top of one another, out of order.

"There'll be someone going around the Earth trying to figure out what happened to us," Eddy said. "There'll be big debates about it."

"Well, we were stupid and killed ourselves. On a grand scale," Keller said. "You rule the world, and then you die."

We all chuckled at this prediction—mass extinction, by this point, having become something of a macabre inside joke. Just past the spoil, we reached the end of the road, which was lined with piles of white dirt too tall to see over. Clambering over them in search of outcrops, we were confronted by a strange view on the other side: an enormous field of coal, pockmarked with holes. The black earth had been dug at regular intervals to create thousands of pits, all the size and depth of shallow graves. Each one had its own mound of white earth beside it, as if waiting to be filled. No one could explain what they were. A

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