PHOTO: PETER MURPHY

BACK FROM THE DEAD

The once-moribund idea that volcanism helped kill off the dinosaurs gains new credibility

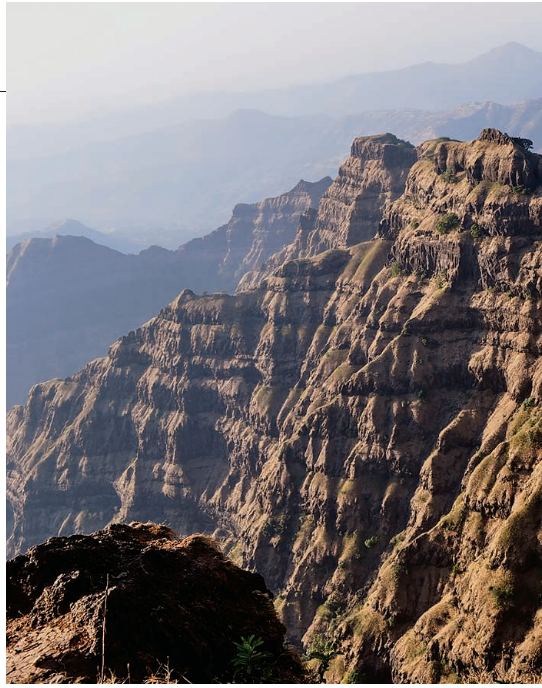
By **Richard Stone**, *in Maharashtra state, India*

Gerta Keller's latest findings have pulled her from the fringe back to the frontier.

Perched on a bluff on the Deccan Plateau here in southwestern India, the ruins of Sinhagad Fort command a sweeping view of sienna-hued volcanic ridges draped with haze from the nearby metropolis of Pune. Turn back the clock nearly 66 million years, and this vantage point was hell on Earth. Then, India was an island straddling the Réunion hot spot: a magma fountain gushing from deep in the earth that, for some 750,000 years, flooded an area the size of Mongolia with lava in one of the largest episodes of volcanism in Earth history.

Today this rugged terrain is ground zero for a long-running and bitter scientific debate, centered on the cataclysmic extinctions that took place at roughly the same time. One camp argues that Deccan volcanism spewed enough carbon dioxide to send temperatures soaring globally while sulfur fumes turned the oceans to acid, with lethal results for three-quarters of Earth's life forms, including all nonavian dinosaurs. The other camp, in the ascendancy for decades, blames the die-off on a single killer: the impact of an asteroid.

Online this week in *Science* (http://scim.ag/BSchoene), volcanism gets a big boost, and so does one of the most contentious figures in the debate, Princeton University paleontologist Gerta Keller. In the paper, she and her colleagues report precise dates for the main phase of Deccan volcanism. Countering claims that the lava outpouring took place too early to have played any role in the extinctions, they show that it straddles the Cretaceous-Paleogene boundary (KPB): the geological moment when many creatures from the age of dinosaurs vanish from the fossil record. "It's an important paper," says Paul Renne of the Berkeley Geochronology Center in California. "It shows that most of the action happened over a limited time range" and that older ages ascribed to the Deccan flows are wrong.



The new findings mark the latest step toward redemption for the volcanism hypothesis. The idea was sidelined in 1991, when remnants of a 300-kilometer-wide crater called Chicxulub were confirmed off the Yucatán Peninsula. This is the scar left by a 10-kilometer-wide asteroid or comet that collided with Earth a mere 32,000 years before the Cretaceous ended. (Renne and others nailed the impact's timing in a report in *Science* last year.) Since then, however, growing evidence has hinted that the asteroid might not have been the only killer at work. Of a dozen enormous lava flows known as flood basalts in the geological record, four immediately preceded mass extinctions. And many paleontologists argue that well before the Chicxulub impact brought the curtain down on the Cretaceous, a host of species had already winked out or were in sharp decline. "The pendulum has certainly swung" toward a role for volcanism, Renne says.

More and more scientists now embrace the notion of a one-two punch at the KPB: Deccan volcanism crippled many species and extinguished some before the Chicxulub bolide came along to deliver a knockout blow. "The new paper in no way diminishes the role of the impact," says Shen Shuzhong, a paleontologist at the Nanjing Institute of Geology and Palaeontology in China. But a link between Deccan volcanism and the mass extinction, he says, is now "hard to deny."

Hard, maybe, but not impossible. Key figures in the impact camp refuse to countenance any role for volcanism—and are unswayed by the new findings. "The crux of the matter is this: Is Deccan a factor in the extinctions? I say it's not," says Alan Hildebrand, a geologist at the University of Calgary in Canada. "What I see are people desperately trying to find something that doesn't fit the impact hypothesis." Impeding any armistice is the divisive figure of Keller herself.

"I MAY BE A BIT STUBBORN," Keller says. "But there is a silent majority who knows that I am right." Now 69, Keller grew up on a dairy farm in Switzerland with 11 brothers and sisters. In 1964, desperately poor and believing she had no future at home, the teenager took off backpacking for several months and ended up in Australia. In Sydney, she says, she was shot by a bank robber attempting to carjack her Volkswagen. As she lay near death, a priest twice urged her to confess her sins. "I said, 'No, I have nothing to confess.' That made me mad, and probably saved my life." A few years later, she left for the United States, and in 1978 she earned a Ph.D. in paleontology and geology from Stanford University.

Keller got her start at a heady time for the geosciences. In 1980, the father-son team of Luis and Walter Alvarez and two colleagues published a landmark paper in *Science* proposing an "extraterrestrial cause" for the KPB extinctions. Their smoking gun was high levels of iridium turning up in KPB sediments. Because the element is depleted in Earth's crust but abundant in meteorites, they argued that it had to have originated in an asteroid that collided with Earth and flung iridium-laden debris across the planet.

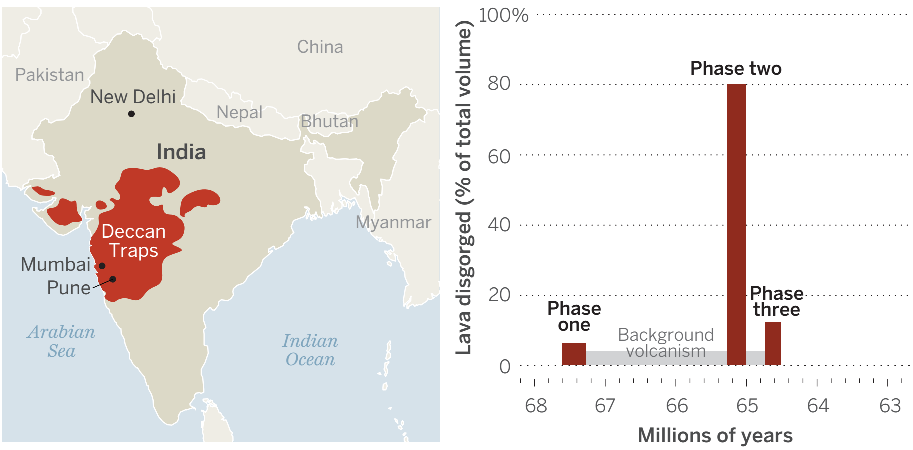
The provocative idea captured the public's imagination but got a cool reception from scientists who favored a gradual extinction trigger, such as protracted volcanism. Paleontologists, for instance, argued that the fossil record hinted at a prolonged die-off, not a sudden death blow. The dispute quickly became personal. Luis Alvarez, who had won the Nobel Prize in physics in 1968 for his discovery of resonance states in subatomic particles, famously ridiculed paleontologists as "stamp collectors." One proponent of a volcanic explanation for the KPB extinctions, paleontologist Dewey McLean of the Virginia Polytechnic Institute and State University in Blacksburg, says his encounters with the elder Alvarez in the early 1980s were so venomous that they wrecked his career and his health. "Luis was not a gentle person," Renne says. "A lot of people with opposing views were pushed around."

After moving to Princeton in 1984, Keller ventured into the maelstrom, believing that fossil marine life, among other indicators, didn't square with the impact theory. "The data showed that the mass extinction could not be instantaneous," she says. Her first run-in with the impact camp came in 1988, at a meeting on global catastrophes in Snowbird, Utah. When she started to deliver her talk, she says, "I didn't even get past my introduction and I was already being shouted down." Anyone who had the temerity to question the impact theory, she says, "was simply told, 'You don't know what you're doing. This is all stupid, it's ridiculous, blah, blah, blah.' "

Keller herself was developing a reputation for obduracy. As a graduate student in the 1980s, Hildebrand, energized by the impact hypothesis, set off in search of a crater. "Gerta made a big point of telling me that I was wrong—that I was wasting my time," he says. Throughout that decade, Hildebrand and others turned up rock ejected by the impact in Haiti and elsewhere, but the crater eluded them. In fact, it had already come to light, although almost no one had noticed. In 1978, geophysicists surveying for an oil company had discerned a vast, buried scar centered in the Gulf of Mexico near the Yucatán village of Chicxulub.

Sea of fire

The lava flows of the Deccan Traps span an area the size of Mongolia. New findings show that most of the lava was disgorged over a 750,000-year period precisely when many denizens of the age of dinosaurs vanish from the fossil record.



CREDITS: (PHOTO) GERTA KELLER; (DATA) GERTA KELLER

Team member Mike Eddy samples a layer that could contain zircon-rich ash from the awe-inspiring Deccan Traps near Pune.

PHOTO: GERTA KELLER

Hildebrand got wind of the find in 1990 and contacted one of the scientists; together they obtained core samples from the oil company and found shocked quartz and glass spherules that could only have been forged in the cauldron of a bolide impact or a nuclear explosion. Teams fanned out across Yucatán and found outcrops left by the geological calamity, including rhythmically layered sandstone, a couple of meters thick, just below the iridium-rich stratum. Several researchers suggested that the layers were deposited by a gargantuan tsunami unleashed when the bolide slammed into the ocean.

When the tsunami evidence looked overwhelming, Keller was ready to move on. "I thought I'd had it by then," she recalls. But she says that Charles Officer, a geologist now retired from Dartmouth College and an implacable impact critic, badgered her for days to make a field trip to Yucatán to inspect the KPB outcrops for herself. She relented, but her adversaries refused to give her the coordinates. That only stiffened Keller's resolve.

Mexican researchers helped her locate the crater's KPB layers, and several dozen field trips to Yucatán over the next decade generated extraordinary claims. She and her colleagues described finding fossils of tiny aquatic life forms and their burrows in the sandstone, suggesting that the sedimentary rock attributed to the tsunami had actually formed over thousands of years. Later, she also claimed that the Chicxulub impact occurred 300,000 years before the KPB and that its effects would have been too short-lived to trigger the die-off. Most startling, she asserted that multiple, undiscovered impacts contributed to the KPB iridium—but that much of it is of earthly origin.

"She's been fighting the Chicxulub crater" ever since it was found, Hildebrand says. Jan Smit, a geologist at VU University Amsterdam, scoffs at the claims of life forms and burrows in the tsunami sediments: Keller's group mistook dolomite crystals for fossils, he asserts, while the burrows were made "after the tsunami waves subsided." And even Keller's backers shake their heads at the multiple impact theory. To Smit and others in the impact camp, Keller had strayed into the fringe.

BELOW THE RAMPARTS of Sinhagad Fort, Syed Khadri briskly strikes a volcanic outcrop with a rock hammer. Trapped inside, he hopes, are clues to what killed the dinosaurs. "There are no fossils in this basalt, of course," says the geologist, from Sant Gadge Baba Amravati University in India. "We're looking for zircons."

A few months earlier, Keller, Princeton geochronologist Blair Schoene, and a few others had joined Khadri on a zircon hunt. When zircons crystallize, they trap uranium atoms, which turn the tiny crystals into precise timepieces that run for billions of years. The radioactive element decays into lead at a known half-life, so the ratio of the two elements' isotopes reveals how long ago the crystal formed. Zircons are scarce in basalt but common in the silica-rich ash of explosive volcanic eruptions. Schoene's team found such ash—overlooked by past geochronologists, he says—embedded between layers of flood basalt. The zircons he and his colleagues culled have allowed them to conclude that the main eruptions began about 250,000 years before the KPB and lasted roughly 750,000 years.

Smit contends that the date Schoene and company arrived at for the onset of the main phase—66.29 million years ago—could be spurious. It may be "from a much younger vein [of lava], crossing the old lava flows like a sill," he says. That's "very unlikely," Schoene says: Sills are seldom seen in the Deccan Traps, and the layers his group sampled seem to have been deposited in chronological order. He adds that the dates "perfectly" match earlier paleomagnetic work led by Vincent Courtillot, a professor emeritus of geophysics at Université Paris Diderot and the Institute of Earth Physics of Paris. "Of course, more datable samples from the base of the Deccan are the best way to answer Jan's skepticism," he says.

Smit and Hildebrand dispute another central tenet of the Deccan hypothesis: that many species were in trouble before the Chicxulub impact. There's "lots of arm waving," Smit says, but "no evidence whatsoever." He doubts that the Deccan eruptions "had more influence on biota than just a few minor temperature changes." In contrast, he and Hildebrand say, the impact's legacy in the fossil record was instant and dramatic: Marine species vanish abruptly, and ferns, the ultimate survivor, dominate the land record right after the catastrophe.

The Princeton team concedes that their latest result doesn't clinch the case. For example, it does not reveal whether the eruptions took place as a steady trickle or as brief, massive outpourings, which would have had a much more profound impact on the environment. "We really need to get at the tempo," Renne agrees.

Courtillot, a longtime champion of Deccan volcanism, says paleomagnetic data and other evidence suggest that massive lava pulses—some exceeding 10,000 cubic kilometers, 100 times larger than any historic eruption—were released in a flash: possibly less than a decade. "The gas output of such flows was comparable to that of the impact, and there were many such flows," he says. To test that idea, Schoene and Keller are heading back to the Deccan Traps next month in search of more zircons, which they hope will yield finer detail about the duration and size of the lava pulses. "If we can nail down the flows that initiated the extinctions," Keller says, "then we really are in business."

The next step would be to show exactly how those eruptions might have wiped out species. "We need to explain how you get the global mass extinction from volcanism," she says. Her team is now looking for evidence of pulses of ocean acidification accompanying Deccan eruptions in the 50,000 years before the KPB. Already, though, many of her peers say that the new findings have pulled Keller from the fringe back to the frontier. At least, she says, with a laugh, "I don't expect hostile receptions anymore." ■