The NEXT SPECIES

The Future of Evolution *in the* Aftermath of Man

MICHAEL TENNESEN

The NEXT SPECIES

MICHAEL TENNESEN

The Future of Evolution in the Aftermath of Man

SIMON & SCHUSTER
New York London Toronto Sydney New Delhi

Contents

To Annabelle, my mother, who loved the oceans, the mountains, the deserts, the birds, the animals, and *the people.*

Every part of this soil is sacred in the estimation of my people. Every hillside, every valley, ever
plain ~~and grove, has been hallowed by some sad or happy event in days long vanished.~~

—Chief Seattle, 1854

We live in a zoologically impoverished world, from which all the hugest and fiercest and strange
forms have recently disappeared.

—Alfred Russel Wallace, 1876

THE GEOLOGIC TIME SCALE

Note: "mya" means "million years ago"

EON	ERA	PERIOD	EPOCH
Phanerozoic (541.0 mya to present)	**Cenozoic** (66.0 mya to present)	**Quaternary** (2.58 mya to present)	**Holocene** (11,700 yrs to present) **Pleistocene** (2.58 mya to 11,700 yrs)
		Neogene (23.03 to 2.58 mya)	
		Paleogene (66.0 to 23.03 mya)	
	Mesozoic (252.0 to 66.0 mya)	**Cretaceous** (145.0 to 66.0 mya)	
		Jurassic (201.3 to 145.0 mya)	
		Triassic (252.0 to 201.3 mya)	
	Paleozoic (541.0 to 252.17 mya)	**Permian** (298.9 to 252.17 mya)	
		Carboniferous (358.9 to 298.9 mya) (**Pennsylvanian** and **Mississippian**)	
		Devonian (419.2 to 358.9 mya)	
		Silurian (443.4 to 419.2 mya)	
		Ordovician (485.4 to 443.4 mya)	
		Cambrian (541.0 to 485.4 mya)	

SUPEREON	EON	PERIOD
Precambrian (4600 to 541.0 mya)	**Proterozoic** (2500 to 541.0 mya)	**Ediacaran** (635.0 to 541.0 mya)
	Archean (4000 to 2500 mya)	
	Hadean (4600 to 4000 mya)	

Prologue

WE HAVE NO IDEA WHAT WE'RE IN FOR

IT WAS MID-MORNING, June, during the tropical dry season, as the Peruvian army Mi-17 helicopte lifted us off from a military base near the town of Ayacucho, Peru, on the western side of th Andes Mountains and slowly ascended toward the crest of the magnificent range. The expansiv dry terrain below was spotted with cactus, shrubs, and wide stretches of open space, interrupte only by small villages covered in a fine layer of the local dust.

These slopes constitute the eastern boundary of the Atacama Desert, one of the driest spots o earth. It gave no hint of the verdant rain forest that awaited us just beyond the summit of th Andes. But as the helicopter crested the mountains, the eyes of the passengers—a military cre and an international team of scientists—opened wide at the sudden appearance of the headwate of the Amazon River and the thick blanket of deep green vegetation that cloaked the mountains o this much wetter terrain.

Inside the helicopter, the group of celebrated biologists, part of the Rapid Assessment Progran had been sent here by the Washington, DC–based environmental group Conservatio International to do a quick and dirty survey of the wildlife in the tropical forest region of th Vilcabamba, one of several mountain ranges within the eastern Andes under threat by oil an mining interests. Conservation International wanted to know if the area was rich enough in th number of plant and animal species to warrant the use of the group's limited funds to save it. Th more species there were, the more likely that some would survive the current environmental crisi

I sat with the scientists on uncomfortable metal benches bolted to the wall, gear piled hig around us. Most were dressed in khakis with an assortment of high-top boots, a few beards, an several parkas. They all tried to peer out the cloudy glass portals and the open door of the cabi excited by their first look at the tropical forest they'd come to study. A Peruvian soldier, wearin no seat belt, one arm hooked through a wall handle adjacent to the open door, was perche dangerously with his legs and gun dangling out the helicopter. Insurgents had wounded one of h comrades the day before, and he scanned the forest below, looking for trouble.

Our view stretched eastward over the Amazon Basin where the sun had already begun to he the tropical forest, turning its moisture into towering thunderheads, which by noon would begi to assault the eastern face of the Andes with wave upon wave of mist and rain. The result of all th water was a lush tropical menagerie, an area scientists consider to be the most biologically diver of all the remaining forests on earth. The enormous number of species of fauna and flora in th Andes and in the adjoining Amazon Basin is as vital to the health of the tropics as it is to the worl This area gave birth to many of the terrestrial plants and animals on earth and is thus responsib for much of the world's species diversity—its "biodiversity." Scientists tell us that nature i currently heading toward one of the major catastrophes of its existence, a deadly crisis brought o by the land use activities of man, resulting in the plummet of species numbers. Our best hope an why so many scientists were aboard this helicopter was that the tropics could serve as a reposito from which nature could resurrect replacements in the future.

~~There is reason and precedent for this hope, which is why these scientists are studying~~ th specific landscape: during past ice ages, for example, most Andean animals and plants moved dow from the precipices and held out in isolated pockets of rain forest at lower elevations. Whi glaciers scoured much of the earth, closer to the poles, destroying all life that could not get out the way, the Andes and the Amazon functioned as a warm safe haven from this frozen assault.

Today, the eastern Andes Mountains is one of the few places on earth where new species animals not yet discovered by science, still abound. The area is classified as a global hot spot, terrain with dense biodiversity, featuring many species found nowhere else in the world. It is i areas like this, in dark and difficult corners of the globe that scientists hope nature might surviv man's current assault, and new species could reappear.

The mountainous terrain below our helicopter featured an area known as "cloud forest" wher trees were shrouded in mosses and ferns. The canopies were filled with orchids and bromeliac that cast their roots into the leaves and humus in the crooks of the trees or into the bark of tl branches in place of dirt.

Many of the species here had what Wake Forest University biologist Miles Silman described "shoestring distributions." The area where they can grow and reproduce may stretch horizontall for hundreds of miles but vertically only a few hundred feet. "I can throw a rock over th elevational distribution of some of these plants," said Silman. He fears that climate change coul push species uphill too fast for them to adapt.

There is a reason they call this "cloud forest." It could take several days to land in such an are because of the constant cloud cover. The first day we tried, our army helicopter was turned bac by the weather, and the pilot decided to visit the Asháninka Indians instead. Tribal members al came out to greet us. Their faces and arms were streaked with berry juice, a jungle version makeup. A woman offered us *chicha*, a liquid made from yucca that is masticated and fermented b the tribal women, which the pilot told us to accept, to avoid gravely insulting the communit The Asháninka still took game from the local forests and fish from nearby streams.

On the third day, the clouds finally broke and we landed. I was one of the first people out of th helicopter, and my boots sank deeply into the boggy soil. I turned to the scientist behind me an told her I thought this was the wrong place. But she would have none of my hesitancy. "This is it, she said, and gestured for me to get going. Within hours we'd unloaded the gear and hacked ou way with machetes through the forest to a knoll where we cleared an area and set up a function though very damp camp.

The tropical Andes contain about a sixth of the world's plant life in less than 1 percent of i land area. White-faced monkeys, spider monkeys, and mantled howler monkeys swing through th trees and fill the damp air with their screams and roars. Puma, bear, white-lipped peccaries, an mountain tapirs patrol the woods looking for dinner, while the birds, bats, and butterflies shadov their movements. There are more than 1,724 species of birds in an area the size of New Hampshi —better than double the number found in Canada and the US combined.

The Vilcabamba Range is cut off from the surrounding mountains by the deep valleys of th Apurímac and Urubamba Rivers. Rising like an island in a sea of jungle, it is as isolated as an islar surrounded by ocean.

Life is unique in the tropics. Animals often specialize, living off a single plant or groups plants. Some flowers have long, curved tubes that can only be pollinated by certain species hummingbirds with similarly curved bills. But there are also cheaters, like the flowerpiercer, bird that can use its hooked bill like a beer can opener, notching little holes at the bases of flowe so that it, as well as bees and small hummingbirds, can get at the nectar without having to g through the flowers' long tubes.

One night about a week into our trip when the rains started coming down, the reside herpetologist Lily O. Rodríguez and I put on headlamps and headed out into the deluge lookin for new species, since rains brought out the different frogs and amphibians. Rodríguez starte telling me stories about how these animals learn to specialize in the face of intense competitio She said that some of the frogs here don't have tadpoles; they sit on their eggs like chickens. Oth frogs store their tadpoles in leaves above streams into which the tadpoles fall once they hatch. An then some tadpoles have huge mouths to hold on to their favorite rocks when the streams run to fast.

The rains grew heavier and we put on waterproof army ponchos over Gore-Tex parkas. Bu this didn't stop Rodríguez from climbing out on a wet, slippery tree limb when she thought sh heard a new frog croak. She found nothing out on the tree limb that night, but she came acro twelve new species in the course of our four-week visit.

The wonder of evolution is exemplified in these rarefied, verdant corners, where life adapts t tiny ecological niches of nature that require elaborate maneuvers for others to take advantage o The question is: Will nature provide the necessary niches and maneuvers to meet the future? Wi the tropics be part of the rescue, if there is one? And will modern man be along for the ride?

* * * *

The palpable haste of modern biologists is due partly to the fear that we may be at the start of mass extinction event—a loss of over 75 percent of plant and animal species. Such events hav occurred only five times in the past 600 million years, when animals first appeared in the foss record. And now scientists suggest that a sixth mass extinction may be under way, given the know species losses over the past few centuries and millennia. A recent report in the science journ *Nature* from biologists at the University of California, Berkeley, states that we could reach th extreme of a mass extinction in as little as three centuries from now if current threats to species a not alleviated.

It took *Homo sapiens* less than 200,000 years to reach a burgeoning population of one billion 1800, but by 2000 we topped off at six billion, and by 2045 we are projected to reach nine billio It is an unprecedented surge of growth, with unimaginable risks and innumerable side effects—th wellspring of a raging crisis.

And yet it is a dilemma man appears to ignore, though it is becoming more difficult t disregard as the list of earth's endangered plants and animals keeps growing due to our multip assaults on the environment. We have become a deadly virus to nature.

Our massive overpopulation and accompanying decimation of earth's natural resources, pursued unabated, may lead to man's own demise. Yet, as great as our footprint has been, from geological perspective, we've done all this damage in a brief moment. If one looks at the enti history of earth as a twenty-four-hour day, we only entered the picture around the last seconds o that day. We work fast.

Of course, earth will recover, no matter how devastating our brief visit here. After all, jus because it may mean the end of man, it won't be the demise of all biological life. Life is resilien Plants, animals, and microbes will survive, adapt, diversify, and proliferate. New plants will evolv to vanquish our monocultures of corn, wheat, and rice. With far fewer animals around, thos species that survive the bottleneck of extinction will move into newly abandoned spaces. Wit little competition, they will thrive and rapidly evolve.

It's all happened before.

Recoveries followed all the mass extinctions, no matter their causes. The Ordovician extinctio event 443 million years ago destroyed 86 percent of species with a barrage of alternating glaci cycles. The Devonian event 359 million years ago took out 75 percent of species with a one-tw punch of global cooling and global warming. The Permian event 252 million years ago destroye 96 percent of species with a Siberian supervolcano. The Triassic event 200 million years ago too out 80 percent of species with a combination of global warming and ocean acidification. Th Cretaceous event 65 million years ago destroyed 76 percent of species with the impact of a asteroid. Though we have identified the prime suspects here, each of these mass extinctions ha multiple causes.

The best known, the Cretaceous extinction 65 million years ago, was the primary result of a asteroid impact, though it had help from a supervolcano, the Deccan Traps in India—traps bein large regions of volcanic rock with step-like plateaus and mountains that are typical of flood basa eruptions. The Permian extinction 252 million years ago, the child of a volcano, also had hel from the collapse of ocean currents, among other causes. Yet, despite their enormous destructior the Permian extinction opened the door for the dinosaurs, and the Cretaceous extinction opene the door for mammals and man.

Extinction is a powerful creative force, says Douglas H. Erwin, a paleobiologist at th Smithsonian Institution. In his book *Extinction: How Life on Earth Nearly Ended 250 Million Yea Ago* he writes, "From the wreckage of mass extinctions the survivors are free for bursts evolutionary creativity, changing the dominant members of the ecological communities, an enabling life to move off in new and unexpected directions."

Anthony Barnosky, a professor of integrative biology at the University of California, Berkeley and principal author of the *Nature* paper, says that the critical component in determining if we a headed toward a mass extinction event is the status of critically endangered, endangered, an vulnerable species. "With them, Earth's biodiversity remains in pretty good shape compared t the long-term biodiversity baseline. But if most of them die, even if their disappearance stretched out over the next 1,000 years, the sixth mass extinction will have arrived," he says.

He thinks that if we save the species now considered in trouble, we may have a chance. But ou work at saving endangered species has resulted in many cases of what paleontologists refer to "dead clade walking"—"clade" meaning groups of organisms. An example of lingering species the California condor, which is threatened by lead poisoning, lethal pesticides, and expandin urban areas. It has cost millions of dollars and countless hours of work to preserve critical habita raise captive birds, and release them to the wild—but will the California condor be here for th next thousand years?

And if so, will other birds survive the bottleneck of mass extinction? Will reptiles, fish, insects mammals, and perhaps even man survive? And how will they differ from the current versions their species? That is what we will investigate here.

* * * *

This book looks at past extinction events, the evolution of man and nature, evolutionary chang already under way, and the evolutionary changes likely to occur. Our title, *The Next Species*, is use in its plural sense. We are interested in the next species of marine and terrestrial animals as muc as we are in the next species of man. The research was built on scientific papers, books, as well a personal visits and interviews with experts. Its vision is based on fossil evidence from the pas studies of the present, and expert predictions of the future.

I visited more than seventy scientists from Harvard, MIT, Duke, the Smithsonian Institutio the American Museum of Natural History, UC Berkeley, Stanford, the University of Indiana, th University of London, Oxford University, the Max Planck Institutes, and more. We spoke on th phone with many others.

Many, like Hans-Dieter Sues, curator of vertebrate paleontology at the Smithsonian, think tha extinction is a normal process of life. "Virtually 99.999 percent of all life on the planet has gon extinct," says Sues. "And so will *Homo sapiens*. Maybe in one thousand years we will have figure out how to do interstellar travel, so if things go haywire down here, we can take off and g somewhere else. But it's just as possible we will mess around with our own genome and creat some sort of race of superhumans, and they'll drive us to extinction."

This book looks around the world for lessons in evolution. What can past mass extinctio teach us? Can pristine ecosystems exist in war zones and nuclear accidents? What can 30,000-yea old fossils under Los Angeles tell us about the diversity of life? Will scientists rewild the Americ and Europe with elephants, cheetahs, and lions? Will jellyfish and giant squid dominate th oceans? Does disease fester in a world devoid of its native species? And what about the chances o an escape to Mars?

We'll also explore the possibility of other forms of life evolving. Could isolation in the wake o a mass extinction provide the evolutionary opportunity for another species of man? Will geneti provide our children with better minds, longer lives, and unique bodies? Or will scientists figu out how to upload the human mind, making our bodies obsolete, so that we live on as robots o avatars in a virtual world.

The possibilities abound.

VISIT TO THE PAST

1

A MASS EXTINCTION: THE CRIME SCENE

IF YOU'RE CURIOUS as to what a mass extinction looks like, you might want to visit the remains o the Capitan Reef at Guadalupe Mountains National Park, the highest mountains in Texas. Lif abounded in the seas back then, but the dinosaurs had yet to appear. The creatures that walked th dry land were not as enormous, nor as diversified, as they would become later. The continent were bound together in a single landmass, but as it broke up and drifted apart, the movemen provided the isolation necessary for new species to evolve. Still, life had to sidestep the Permia extinction before it could truly flourish. The story of life's decimation at this point, followed b its resurrection, has multiple lessons for our own predicament.

The Capitan Reef, though long dead, once thrived between 272 and 260 million years ago i the middle of the Permian period, just before the greatest mass extinction the world has eve known. The International Union of Geological Sciences has selected three points within the par as "golden spikes," the standard against which all other rocks of the Middle Permian period ar compared. (The actual markers that indicate these points are brass plaques.)

At the bottom of the trail up to the reef one day, I met Guadalupe Mountains National Par geologist Jonena Hearst. After she patiently answered questions from a park visitor and showed m some maps and geological charts, a process that took twenty minutes, she loaded up her day pac and lifted it onto her back. With a big broad smile she signaled it was time to get going. I followe after her. It was fall, a transitional time in West Texas weather, when mornings bore the chill of impending winter, yet the afternoons carried a remembrance of summer heat. McKittrick Canyo before us cut a slash through the Guadalupe Range, exposing the backbone of the Capitan Reef- one of the most extensive fossil reef formations on earth.

The surrounding terrain was dry, open desert, with cactus and creosote brush sheltering a assortment of rabbits, snakes, and lizards—a marked contrast from the tropical rain forests o Vilcabamba. Whereas the rain forest is full of moisture and life, the desert is bashful about an display of exuberance. Farther up McKittrick Canyon, cottonwoods surrounded a portion of th stream that surfaced intermittently. The trees were full of inviting autumn colors, but our pat quickly pulled away from the stream and veered up a steep embankment toward the Capitan Re above us.

What we saw of the reef exposed here displayed the calcified remains of an enormous formatio of shelled creatures and sponges that once lay beneath an ancient sea, not unlike the coral reefs o today. A huge fault lifted a section of the reef high into the air, brandishing the dark rock for all t see. The trail was steep—a gauntlet of narrow switchback turns, full of slippery boulders tha tested one's stamina and balance. Yet the site was still quite popular, particularly with geologist and paleontologists, for it led into the fossil remains of an ancient world.

Park geologist Hearst was the keeper of this treasure, and was astute and knowledgeable abou its intricate secrets. But she was as exuberant as she was scholarly. She told me she had last hike up this reef just two weeks earlier, yet she wore a big smile despite some heavy breathing. “It’s geological Disneyland,” she proclaimed. “Every time I go up there, I learn something new. How many times have I been on that ride, you ask?” She shook her finger toward the reef. “Don’t know but I want to do it again!”

The hike began at the bottom of an enormous depression known as the Delaware Basin, which spread out into Texas. The reef had formed over a distance stretching many miles around the lip of the basin, the horseshoe mouth of which once pointed out to an ancient sea. A quarter of a billion years ago, this reef was still glowing with a halo of life formed by millions of juvenile fish and other marine creatures that once used the nooks and crevices of the reef to avoid large predators.

Back then, two enormous continents—Laurentia (made up of North America, Europe, and Asia) and Gondwana (made up of South America, Africa, Antarctica, and Australia)—formed the terrestrial landscape at the surface of the planet. These two landmasses were on a collision course soon to form Pangaea, the single continent that would take the world through the Permian extinction, an event that came the closest to ending life on earth than at any other time in the last 600 million years.

Our trail told the grand story of life before that event. We scrambled up the loose rock beneath the slopes of the giant reef head. We gained altitude quickly as the trail rose above the desert landscape. This was a deepwater reef, different from the shallower coral reefs most recreational divers are familiar with today. In Permian times, we would have been walking 5,000 feet (1,500 meters) below the surface of the ocean. “A very long snorkel to get to the top,” said Hearst.

As we rose upward, larger boulders and layered outcrops gradually displaced the loose, rocky slopes. Hearst stopped before a large boulder that reached our height and stared at the markings on it. At first I didn’t see anything special; it was just a big boulder. But then she pointed out the many fossils contained in the rock. It turned out that we weren’t staring at a plain rock—we were gazing on the calcified remains of ancient reef animals that had once been bound together in a mass of life.

During the Permian period this gallery of life included flowerlike crinoids, which sat atop stalks attached to the seafloor, their numerous tentacles coated with mucus extended out to capture prey, and you could see the fossil remains of these creatures in this rock. There were also bryozoans, small animals that superficially resembled corals, which grew in tightly packed colonies resembling intricate fans, lacy fronds, or fruitlike displays that accumulated into massive stony buttresses. Also here were clamlike creatures called brachiopods, which were filled with a tangle of filaments that helped the animal sift food from the water but which would have made a poor clam chowder. There were numerous species of sponges as well as nautilus-like creatures housed in large spiral shells. The boulder was filled with such animals, surrounded by algae, which acted as cement to hold everything together. As she pointed to other rocks nearby, my astonishment grew. All the boulders housed similar amazing displays.

From the base of the reef we pressed on up the trail. As we approached the part of the reef formerly within the reach of sunlight and the energy of the waves, the reef fauna began to change from marine communities dominated by sponges and bryozoans to those dominated by algae and large clamlike gastropods.

Toward what was once sea level, the sponges disappeared. We entered the intertidal zone where outgoing tides would have periodically exposed the reef to sunlight and air, and this produced still more shifts in the animal communities. Ahead we could see the remains of limestone barriers islands. Behind the barrier islands were sand and gravel bars cut through by tidal channels, an beyond that the dry remains of a large lagoon facing a shoreline of salt flats.

The Permian period stretched from 298 million to 251 million years ago, the reef thrivin across the West Texas terrain along the margins of what was once a warm tropical sea. In it prime, it would have been about four hundred miles in length.

Reefs are among the most biologically diverse of any ecosystems. They are the rain forests the sea. Yet they leave more evidence than a rain forest for the paleontologist to study becaus they are made up of hard-bodied organisms that make fine fossils. It's why paleontologists hav made the pilgrimage to McKittrick Canyon for decades to witness what nature has exhume almost intact.

* * * *

It hasn't been that long since man would have looked at this towering monument to the history life and not understood what he was seeing. The recognition and study of fossils in rocks grew ou of an incident in the late fifteenth century when two fishermen caught a giant shark off the coast Livorno, Italy. The local duke sent the shark to Niels Stensen (aka Nicolas Steno), a Danis anatomist working in Florence. Steno dissected the animal and noted how much the shark's teet looked like "tongue stones," triangular pieces that rock collectors had been gathering for ages. Fe at the time would have conjectured that tongue stones or any other fossils might be remnants ancient sea life, but Steno started making a case for it and was widely credited with giving birth the science of paleontology.

The awareness of fossils grew, and in 1815, William Smith, a geologist from the county o Oxford, England, published a complete geological map of England and Wales. He was the first t use fossils as a tool for dating and mapping rocks by their stratigraphy, the lines and layere elements of earth that are visible when sedentary rocks are cut into—though it wasn't until afte Darwin that scientists realized the importance of these fossils to understanding the timing evolution.

Geologists discovered that layers of rock in North America could correspond in time to laye of rock in Asia or even Africa and that similarities in the fossils within them could be used t determine their synchronicity. But what geologists began to realize was that the layered record earth's history at times told the story of evolution a bit differently from Darwin. The maste believed that evolution advanced in tiny increments over multiple generations and that the proce was geologically slow. *Natura non facit saltum* ("Nature makes no leap") was his credo. But othe scientists began to note a number of upheavals captured in the rock record of earth's histor which showed radical, sudden changes in animal fossils.

These upheavals presented an amended look at Darwin's grand scheme, and were known mass extinctions. Evolution continued after them, but mass extinctions reordered nature, abrupt ushering out older forms of life and allowing for the creation of newer ones.

Simple animals without shells or skeletons appeared about 635 million years ago during th Ediacaran period, when oxygen in the atmosphere began to build toward present levels. Sinc then, there have been five mass extinctions. Evidence of the Permian period, which preceded th Permian extinction 252 million years ago, surrounded National Park Service geologist Hearst an me.

Perhaps the most famous of the five extinction events was the one that wiped out the dinosau at the end of the Cretaceous period about 65 million years ago. Scientists long argued over wh had killed off the dinosaurs until, in the late 1970s, a team of scientists at the University ~~California, Berkeley, came up with a theory. Luis Walter Alvarez, a bespectacled Noble Prize-~~ winning nuclear physicist and leader of the team, found unusually high levels of iridium—a heav substance rarely found on the surface of the planet, but quite common in meteorites—in layere deposits of earth that represented the Cretaceous extinction in both Italy and Demark.

Alvarez, his son the geologist Walter Alvarez, and colleagues shook the scientific communit with their announcement that the mystery of the Cretaceous extinction had been solved: a asteroid got the dinosaurs.

Scientists were at first skeptical. Older hypotheses cited volcanism or glaciation as the primar cause of this mass extinction. But eventually high levels of iridium were found at more than on hundred sites, all marking the Cretaceous extinction, and the evidence couldn't be ignored. Bu where was the crater?

The Alvarez team went looking for a depression somewhere on the planet big enough to hav fit the job. The team calculated that the asteroid must have been about seven miles in diameter. I June 1990, a decade after the original Alvarez proclamation, geologists discovered a huge crate underlying the northern tip of the Yucatán Peninsula near the town of Chicxulub ("Chick-sha loob"), Mexico, from which the crater eventually took its name.

The crater revealed that the asteroid must have been about 7.5 miles (12 kilometers) wide ar was traveling about 44,640 miles per hour (20 kilometers per second) on impact, roughly twen times the speed of a bullet. The collision would have released a million times more energy tha the largest nuclear bomb ever tested.

The impact blasted thousands of tons of rock as well as the mass of the asteroid back into th atmosphere, with some elements going into orbit, while others returned to the ground in barrage of flaming meteors. These fireballs ignited the verdant late Cretaceous landscape, burnin half the earth's vegetation in the weeks following the impact. Dust along with the smoke from th fires obscured the light of the sun, dealing a deadly blow to plant life.

In the ocean, huge tidal waves spread out to the continental shores, leaving a line of beache and bloated dinosaurs skewered on shoreline trees. Scavengers had a field day on the plentif carcasses. After the initial fires burned out, the earth descended into a period of perpetual nigh caused by a blanket of smoke and dust in the air. Trees and shrubs began to die, as did the animal that ate them and the carnivores that ate the plant eaters. The Cretaceous extinction killed off th dinosaurs and many but not all of the mammals.

* * * *

At the top of the Capitan Reef, we looked out over the fossils, rocks, precipices, and the valle below us, and imagined life over 250 million years ago at the pinnacle of the Permian period. Dr land, which was then about fifteen miles northwest of the reef, was growing drier. The lush swam forests that had existed before the Permian had been replaced by conifers, seed ferns, and othe types of vegetation that were drought-tolerant. Giant cattail-like trees grew up to eighty fee Ten-foot relatives of the centipede splashed through inshore water.

The first vertebrates had crawled out onto the land only about 100 million years earlier. Gian amphibians, which roamed the marshlands, were up to six feet in length and two hundred pound in weight. They sucked down dinner with enormous mouths filled with sharp teeth, tossing the captives little by little back into their deep throats, like a crocodile or alligator would. There wer flying lizards and large armored herbivores the size of oxen. There were a number of sharks in th

Permian oceans, the most bizarre being *Helicoprion*, which had a spiral jaw fitted with backward ~~leaning teeth that looked like a buzz saw. Primitive pelycosaurs about ten feet (three meters~~) lon with smooth bodies spread over much of the land with giant swordfish-like fins on their back fo capturing the sun.

The Permian world was a lively one, as proven by the numerous fossils that adorn the earthe walls of McKittrick Canyon. But something caused the annihilation of most of these animals.

THE SECOND CREATION OF LIFE

The Capitan Reef that decorates the top of the Guadalupe Mountains above McKittrick Canyo is similar to the structure of Mount Rushmore, only carved not with US presidents but with th force of life that thrived before the mass extinction. Yet the rocks in McKittrick Canyon do no display evidence of the end of the Permian.

To see that, Sam Bowring, a bearded and amiable professor of geology whom I visited earlier a MIT, had to travel to China. Bowring showed me a photo of himself and Zhu Zhuli, a Chines researcher, in Meishan, standing on the face of a rock quarry. Zhuli had his feet on a dark line i the rock that represented the end of the Permian. The change in color was caused by a dramat change in the geology and chemistry of the rock. It was the geological boundary line between th Permian and the Triassic periods, the point where one era of life encased in sediments of eart ceased to exist and another was laid down on top of it. In the photo, Bowring stood above the lin in early Triassic ash beds. It is one of the best-studied Permian-Triassic boundary sequences in th world. Fully 333 species have been identified in the fossils below where these two scientists wer perched. But above that line almost all of them disappear, an extinction rate of 94 percent.

John Phillips, a mid-nineteenth-century English geologist who published the first glob geological time scale, found that the fossils were so different on either side of the Permian-Triass boundary that he referred to the line in the stratigraphic layers that Bowring stood above and th difference in fossils on either side as the Second Creation of Life. He never saw the line i Meishan, China, but had studied this event at similar stratigraphic sites elsewhere in the world.

The catastrophe that created this boundary has similarities to the destruction humans a inflicting through greenhouse gas buildup, ocean acidification, and global warming. No, it wasn a giant spectacular meteor falling out of the sky. The primary villain of the Permian extinctio was the Siberian Traps. This eruption occurred about 252 million years ago, according to ne findings from Bowring. At that time a viscous magma flowed out of the ground and spread ove the land, filling in the valleys and basins around it like honey finds the crevices on a piece of toas The total amount of lava flow was mind-boggling. In one area it grew 6,500 meters thick, almo four miles. "In the end it covered much of Siberia, an area close to the size of the continent United States," Bowring told me.

Still, there was not just a single cause to this extinction. It was more the perfect storm, th coming together of multiple perpetrators, as it has been with other extinction events. The lav that created the traps burned up through an enormous coal reserve at its center, and the heat o the molten lava converted much of the black rock to CO_2. But as temperatures rose, some of tha coal would have converted to methane, which is twenty times more potent a greenhouse gas tha CO_2, and this would have accelerated warming.

The end result of the buildup of CO_2 and methane, among other causes, was one of the fe mass extinctions of insects in earth's history. Their numbers descended from sixty families durin the height of the Permian period to almost zero at the end of it. The air was silent, since birds ha yet to evolve. The coal that had thrived in the marshy environments and plentiful vegetatio disappeared as the earth grew drier. Whole forests and entire ecosystems of plants died but fung flourished, since they fed off the dead plant and animal matter.

Though the asteroid that got the dinosaurs at the Cretaceous extinction may have produced better fireworks display and spectacular tsunamis, in terms of pure raw killing power, the Permia extinction can't be beat. Its witch's brew of toxins poisoned the land for several hundred thousan years. Doug Erwin says that the eruption of the Siberian Traps caused global cooling from th erupted dust, global warming from the CO_2, and acid rains from billowing clouds of sulfu Couple this with ocean acidification and the death of oxygen in the deep seas due to the melting polar ice and the loss of ocean currents, and you have a lethal force that far exceeded th destruction caused by the falling asteroid during the Cretaceous.

The resulting excess CO_2 entered the ocean, making the water acidic enough to preven animals from forming exterior skeletons and destroying most of the reef-making organisms of th Permian seas and most of the reefs. The acidic nature of the seawater, coupled with the lack o oxygen in the deep oceans, wreaked havoc on marine plants and animals. The sulfates tha emerged from the volcanoes reached the upper atmosphere, to be carried afar as sulfuric acid an lethal acid rains. These rains may have been strong enough, suggests Erwin, to kill off many of th terrestrial plants. This totally denuded landscapes over much of the earth's surface. Scientists hav found evidence that much of the rain that followed the Permian extinctions rolled off the land flash floods, since there was no vegetation to contain the flow of water.

Floods skipped across the earth like oil does on a hot skillet, moving in every direction, leavin braided gullies in the rock record. I've witnessed fast-moving desert flash floods that carved ou chunks of road like butter, but desert rains are meager. Imagine flash floods raging in plant-fre tropical or coastal environments where annual rainfalls are twenty, fifty, one hundred inches, o more, racing in full and furious force across landscapes stripped of vegetation, and you'll get a idea of what the floods that followed the Permian extinction must have been like.

But despite the evidence of multiple causes for the Permian extinction, some scientists sti champion their favorite antagonists. Andrew Knoll, a paleontologist at Harvard, thinks that man of the catastrophes—their causes and their results—can be boiled down to one chemic compound, CO_2, the biggest villain of the day, and perhaps our greatest threat as well. In a 200 paper in *Earth and Planetary Science Letters*, Knoll and colleagues tried to work backwards from th extinction event, doing a computerized autopsy of the victims to see if the massacre matched th typical scenario caused by oxygen depletion, a breakdown of the food web, and acid rains, bu none of them quite matched the autopsy except for CO_2. He highlighted a gas that so many toda ignore. "Only 30 percent of the species of plants and animals were tolerant of massive doses CO_2. But after the Permian extinction, that 30 percent suddenly becomes 90 percent of all livin animals."

Estimates vary on how long this extinction lasted. MIT's Sam Bowring sets the duration a about sixty thousand years. The tiny chewing apparatuses of small eel-like animals are some of th first fossils to appear in layers of earth laid down after the Permian extinction. Fossils o *Lystrosaurus*, a mammal-like reptile that looked like a bulldog with tusks, but which survived th extinction and proliferated, mark the beginning of the Triassic recovery.

The irony of the Permian extinction is that though it devastated large portions of the planet, created opportunities in newly emptied terrain. From the resurrection of life after the ma ~~annihilation of the Permian came more-adaptive species, changes in ecosystems, and a world~~ mor diverse than the one before it. Perhaps these improvements could be in our future—if we surviv the extinction.

The processes were similar to what Darwin witnessed in the Galápagos Islands. Of the twelv species of finches he collected, all were adapted from a few individuals from the mainland or othe islands, which had arrived in the Galapágos and proliferated after finding no competition for th banquet of seeds available.

What emerged from the Permian extinction was a similar explosion of new animals and plant Life not only survived, it eventually thrived. By 225 million years ago, the first dinosaurs appeare but by 65 million years ago the group, other than birds, was gone. Their reign on earth laste close to 160 million years, a length of time that the family of man has barely approached.

Though the end was glorious, the millions of years it took to recover from the Permia extinction were excruciating.

* * * *

After a brief lunch at the end of the trail, looking out over western Texas and southeastern Nev Mexico, enjoying the cooler breezes at the top of the range, Hearst and I gathered our gear an headed back down the same path we'd come up on, still taking note of the various changes in th fossil communities, enjoying a second look, knowing them better.

Hearst explained that life as a whole eventually resurrected itself from the Permian extinctio but few of the individual species of plants and animals displayed here in the fossils of the mid Permian made it across the boundary. "Life goes on. Life is incredibly resilient. But my work her has taught me that ecosystems and individual species are so very, very fragile," she said. If history i our teacher, then life in the aftermath of our own era will prove equally resilient, though righ now ecosystems and individual species are rapidly disappearing.

From the height of the trail we looked out over the vast desert below and reflected on our ow situation. We stood in the middle of evidence of a past evolutionary catastrophe and gazed ou over another in progress: our own. Some scientists believe our current situation started at th onset of the Industrial Revolution in Great Britain during the 1700s. This is when CO_2 in th atmosphere began its upward climb, a change mirrored here in the aftermath of the Permian. Bu others date the commencement of our dilemma to 1800, when the human population reached on billion.

Still, others say we entered the present biodiversity crisis during the final moments of the la ice age from about fifteen thousand to twelve thousand years ago, when a substantial portion o the large animals that once existed in North and South America disappeared. Similar scenario took place in Australia, New Zealand, Europe, and Asia with the arrival of man.

Hearst poured some water on a group of fossils, washing off the dust and making them mor defined and lifelike for the moment. Of course, the evolutionary processes that produced the first spark of life were much more complicated.

2

ORIGINAL SYNERGY

IT HAD BEEN RAINING off and on all week at the Cary Institute of Ecosystem Studies in Millbroo New York, a reserve consisting of two thousand luscious acres of mid–Hudson Valley oak, maple and hemlock that the institute refers to as its "campus." I had some big questions to ask—how li got started, how evolution drove its development, what role oxygen played, if evolution was still work in the natural world—and I began my quest at Cary.

A heavy mist rose that day from the wetland patches and crept through the forest propelled by Sunday morning sun. William H. Schlesinger, biogeochemist and president emeritus of th institute, and his wife, Lisa Dellwo, guided me on a birding expedition during a break in the rai through the woods and meadows that abound there. We spotted seventy-six birds before breakfas sixteen species in all. When I couldn't see a bird, they both went to extremes to describe the bir and the place in the woods where it was. Lisa claimed birding cultivates cooperation an communication, and is sadly overlooked as executive training.

On the way back from the woods, I got to talk to Schlesinger about life. Bill is a tall, burly ma with a hearty laugh, a deep, articulate voice, and a head full of chemical formulas. He think chemistry is often underrated and coauthored a book called *Biogeochemistry: An Analysis of Glob Change* with Duke University's Emily S. Bernhardt. The book looks at the role of biolog geology, and chemistry in changes that have occurred on earth.

"The road to life on planet Earth was peppered with more chemistry than people give it cred for," Schlesinger told me.

Though our galaxy, the Milky Way, has existed for 13.7 billion years, our solar system is only about 4.6 billion years old. Our sun, said Bill, is at least a second-generation star—a descendan from a prior supernova, a large star that ran through its nuclear fuel, collapsed, and then explode That explosion blew a whole lot of dust and particles into the cosmos, and the sun and Eart coalesced out of that cosmic residue. A heavy meteor bombardment ensued during the first billio years, added to Earth's mass, and created its moon. The heat of the collisions and the radioactiv decay of the materials melted the whole ball with the heavier chemicals sinking to the molte core, while the lighter elements formed the semifluid mantle and the crust that floats upon it.

One of the critical components for life, Bill pointed out to me, was plenty of water. At the Car Institute, it had just rained, and we jumped around puddles and dodged the occasional delug delivered from the leaf canopy above while Schlesinger explained how we got all this moistur Schlesinger is an excellent orator and teacher, one who is not afraid to hold forth until he sees th light in your eyes that tells him you got it.

Water probably came from the same bombardment of materials that built the planet, h suggested. The heat of the planet would have kept that fallen moisture as steam in the atmospher until the Earth's surface cooled to 212 degrees Fahrenheit (100 degrees Celsius), the boiling poi of water. Afterward, the steam coalesced and the moisture fell out of the sky over several millio years, filling the oceans.

The sun was then 30 percent less luminous than it is today, but the presence of water vapor an CO_2 in the atmosphere produced a greenhouse effect, catching any escaping infrared or he radiation and redirecting it back toward the surface of the Earth. This warmed the plane Without the greenhouse effect, the Earth today would be mostly covered with ice and have a average temperature of about 0 degrees Fahrenheit (minus 18 degrees Celsius).

Another gift of the early arrival of celestial materials on Earth was carbon, a critical element life. “All life on this planet is made of compounds that have carbon in them,” said Schlesinge Carbon forms strong bonds with other chemicals, which is important for building long chemic structures like proteins, cellulose, and DNA. “If you took your body, dried all the water out of i what’s left would be about 50 percent carbon,” he said. “We are basically bags of carbon runnin around on the surface of the Earth.”

How did we get life from carbon molecules? Where did it first occur? These have not been ea questions to answer. Some interplanetary dust and comet ices are found to contain organic matt containing carbon and could have survived entry into Earth’s atmosphere, adding to the carbo already here, he says. Even if the total amount of organic comet matter received by Earth w small, these elements could have served as a catalyst for life.

Scientists and philosophers have debated the question of first life for millennia, though most the explanations have centered on fable or religion. In 1929, British biochemist J. B. S. Haldan and Soviet scientist Alexander Oparin independently suggested that all the ingredients for li existed on Earth from the beginning and that energy from the sun and some unknown process ha gotten life started. In the 1950s, Stanley Miller, a doctoral student in the laboratory of Haro Urey, at the University of Chicago, got more specific when he attempted a famous experiment. H mixed ammonia, methane, and hydrogen—a commonly accepted recipe for the early atmosphe and ocean—in a big laboratory flask and subjected it to an electric charge that simulated lightnin He analyzed samples at regular intervals. The result was a jackpot for Miller and the Urey la after about a week he found simple organic molecules in the flask. Life could be produced in laboratory. He had cooked the infamous primordial soup.

But fame was fleeting. Miller had fashioned his recipe after Jupiter and some of the out planets, but those models proved to be an inaccurate representation of early Earth. More realist versions didn’t do as well, either, and the idea that you could cook up life like soup fell out favor.

But if soup didn’t initiate life, then what did? Scientists turned to the oceans for answers.

* * * *

Possible solutions emerged in the early 1970s when scientists noticed rising plumes of warmi water along a deep ocean crack near the Galápagos Islands, the same islands that fostered Darwi theory of evolution. In 1977, the US naval submersible *Alvin* dove down 7,000 feet (2,100 mete to investigate deep-ocean geysers and found a wonderland of giant clams and mussels as well eight-foot-long tubeworms. The sheer abundance of life at that depth was astonishing—a tropic rain forest of ocean species. Here, eyeless shrimp and snails munched on mats of bacteria th thrived on sulfur compounds. These underwater geysers generated supplies of energy for th plants and animals, rather than the sun, whose light didn’t reach this depth.

Scientists have since explored over two hundred of these geyser systems in the oceans. Some the most remarkable have been along the deep-ocean ridges of the Pacific, Atlantic, and India

Oceans. At these ridges, the seafloor spreads outward along a rift fed by hot magma below, th birthplace of new land on earth. At such places, researchers found colossal deepwater chimney known as black smokers, some as tall as skyscrapers, pumping what appeared to be billowing blac smoke into the sea. It wasn't real smoke, of course, but boiling metal sulfides welling up from th magma below, the acidic mixture oozing into the water at 662 degrees Fahrenheit (350 degree Celsius).

Was this eerie place with its bizarre cast of characters where life originated? Though boilin sulfides hardly sounded like a Sunday buffet, there were certain advantages. The ocean depth would have shielded life from the UV radiation that was then pummeling the ocean surface as we as the land a few billion years ago. Michael Russell at NASA's Jet Propulsion Laboratory i Pasadena, California, thought the mixture too acidic to be involved. So he came up with a theor for a milder first-life solution by looking for another type of geyser that had a gentler origin.

His theoretical answer arose from the slower movement of fresh crust across the seafloo exposing rocks from the mantle. Russell's candidate for the prime mover wasn't an acidic mixtur of superheated waters; it was the reaction of freshly exposed rock with seawater at a relative cooler 210 degrees Fahrenheit (100 degrees Celsius).

Seawater expanded the rock, creating fissures and cracks, which drew in still more seawate This process released energy as heat and large amounts of hydrogen and methane gas. This create another type of hydrothermal geyser, which some called white smokers, or more accuratel alkaline vents. Rather than creating a black chimney with a single orifice belching blac superheated smoke, these vents were complex structures with mazes of tiny compartments th exuded warm alkaline water to the surrounding cold seawater.

Life could have arisen from sulfidic submarine hot springs situated some distance from the dee oceanic ridges. Scientists thought that four billion years ago life could have emerged there from mass of bubbles, each bubble containing hot mineral-laden solutions.

Around the turn of the twenty-first century, the research vessel *Atlantis* and its human-occupie submersible *Alvin* found this exact type of geyser about nine miles (fifteen kilometers) from th Mid-Atlantic Ridge. Dubbed the Lost City, these vents stood like ornate structures up to tw hundred feet (sixty meters) in height, poking up into the vast darkness. At this depth hydroge could more freely bind to carbon dioxide to form organic molecules. First life was not a single ce but a rocky labyrinth of mineral cells that produced complex molecules, including the formatio of proteins and eventually DNA molecules, generated by the energy of the warm vent fluids.

As we came to the end of our bird walk at Cary, Schlesinger said that this made sense. He ha one caveat: he favored a more neutral solution for first life. "Life can tolerate a wide range of pH but really acid conditions [low pH] are likely to oxidize organic materials and really alkalin conditions break down cell membranes," he explained.

OXYGEN MAKES IT HAPPEN

Most scientists agree that, for the first few billion years, life was largely microbial. Yet these littl critters were responsible for most of the genetic heavy lifting. Though we marvel at the size an anatomical complexity of large animals, these features were made possible by cell biology an genetics that were developed in single-cell creatures in much earlier times. According to Harvard Andy Knoll, when complex life first evolved, it had the majority of its DNA already worked out.

For life to really get going, to produce the complex forms of more evolved beings, it had t ~~have oxygen. Two and a half billion years ago, "life" was still in bacterial forms. It had its genetic~~ architecture, but it survived in oxygen-free environments, so it stayed small. But then some of th oxygen-free bacteria evolved into cyanobacteria or blue-green algae, the stuff you sometimes s on polluted waters, commonly referred to as "pond scum."

These guys promoted photosynthesis, a different type of metabolism from what their archa brethren employed. Photosynthesis used sunshine, water, and carbon dioxide to produc carbohydrates and, finally, oxygen. At last, the giraffes and basketball players of the world had chance at survival!

Oxygen was the critical element in the burst of evolution that occurred during the Cambria explosion about 570 to 530 million years ago, when most of the major animal groups sudden appear in the fossil record. At the time the air was murky, since there wasn't enough oxygen t scrub the atmosphere of haze and dust. Without enough oxygen, there was no ozone, either, so th searing intensity of ultraviolet light from the sun could fall without obstruction. Ultraviolet lig breaks up water (H_2O), and since hydrogen (H) is so light, it can slip into space, and there go your ocean. Without oxygen holding on to hydrogen, the world today might look a lot like Mar a dry, dusty, pockmarked planet with no seas, lakes, rivers, or streams and no visible sign of life.

Oxygen gradually accumulated on earth from the photosynthesis of plants. Once oxyge reached critical mass, changes were sudden. If you look at the paleontological record in the soi there is evidence of oxygen-free microbes in one layer, followed closely by oxygen-depende microbes in another layer. This introduction of oxygen, though a boon to most life, spelle destruction for a good deal of earth's early ancestors who excelled without it.

Oxygen made the planet livable. Once established, oxygen patrolled the atmosphere capturi all the hydrogen atoms trying to get away and turned them back into water and rain. Now a ozone shield could form, dampening the intensity of ultraviolet light. All plants and anima depend on oxygen as part of their life cycles, lonely exceptions being the microscopic nemato worms that get along in the stagnant oxygen-free depths of the Black Sea and the creatures th survive on those deep-ocean geysers.

* * * *

The beginning of animal life had to wait about four billion years until atmospheric oxygen beg to rise toward present levels. According to Andrew Knoll, complex multicellular organisms an oxygen first appeared in the fossil record some 580 million to 560 million years ago, during th Ediacaran period. "The oxygen increase pushed earth toward its present state, but it didn't achie it all in one go," he told me when I visited with him at Harvard.

Life didn't burst forth onto center stage in full and varied forms until the Cambrian peri from 542 million to 488 million years ago.

The Burgess Shale, the famous quarry of Cambrian life discovered in 1909 by Charles Walco a paleontologist and former director of the Smithsonian Institution, sits high in the Canadi Rockies on the eastern border of British Columbia. It is perched at about eight thousand feet o the western slope of a ridge connecting Mount Field and Mount Wapta in Yoho National Park near the tourist destinations of Banff and Lake Louise. The view from the rocky slopes of th Walcott Quarry—surrounded by a thick conifer forest, Emerald Lake below, and the snowcappe Canadian Rockies beyond—is one of the finest on the continent. Walcott's daughter, Helen, wrot to her brother Benjamin in March 1912 when she was touring Europe, describing castle