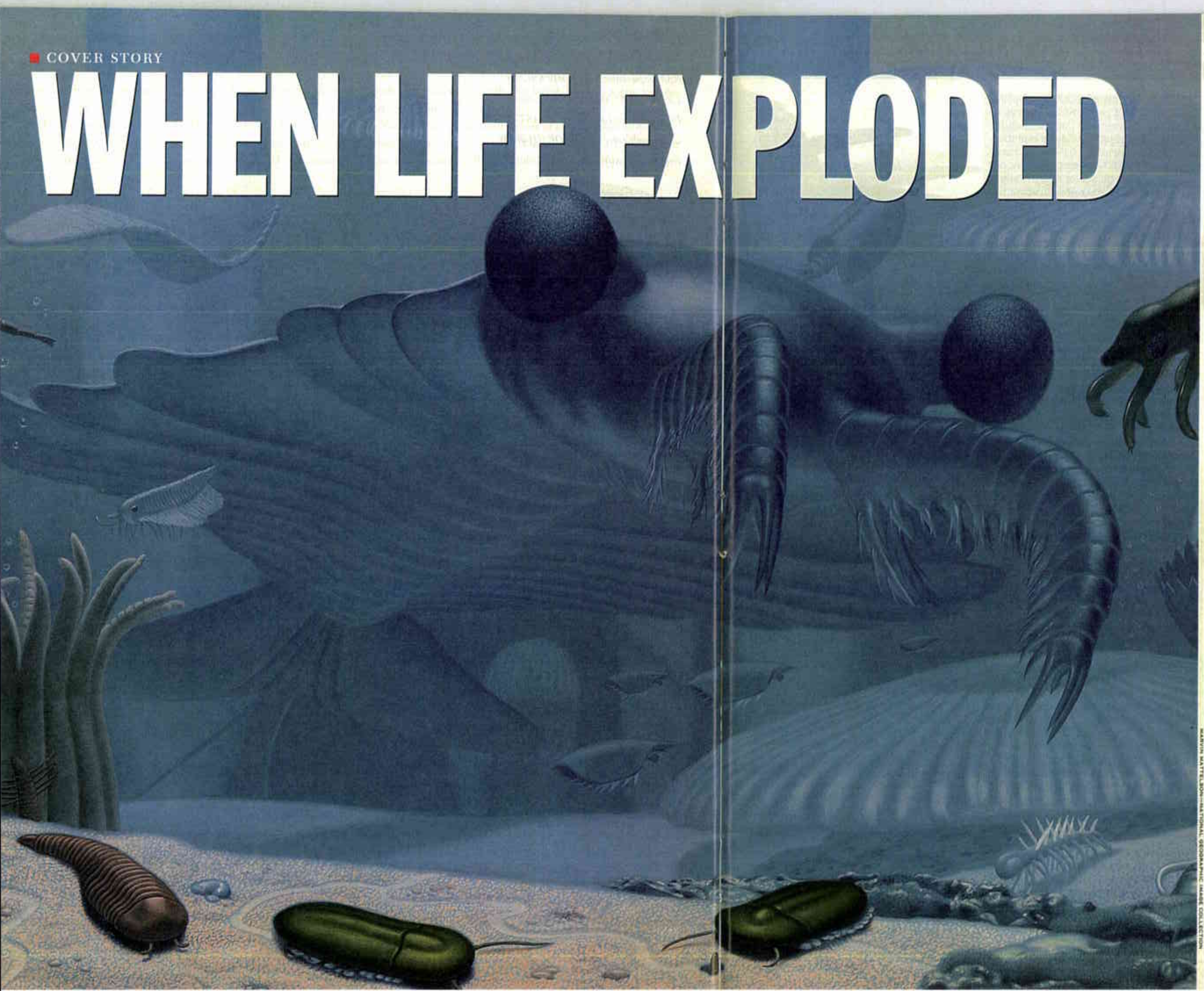
COVER STORY

WHEN LIFE EXPLODED



MARVIN MATTELSON—NATIONAL GEOGRAPHIC IMAGE COLLECTION

For billions of years, simple creatures like plankton, bacteria and algae ruled the earth. Then, suddenly, life got very complicated

By J. MADELEINE NASH

AN HOUR LATER AND HE MIGHT NOT have noticed the rock, much less stooped to pick it up. But the early morning sunlight slanting across the Namibian desert in southwestern Africa happened to illuminate momentarily some strange squiggles on a chunk of sandstone. At first Douglas Erwin, a paleobiologist at the Smithsonian Institution in Washington, wondered if the meandering markings might be dried-up curls of prehistoric sea mud. But no, he decided after studying the patterns for a while, these were burrows carved by a small, wormlike creature that arose in long-vanished subtropical seas—an archaic organism that, as Erwin later confirmed, lived about 550 million years ago, just before the geological period known as the Cambrian.

As such, the innocuous-seeming creature and its curvy spoor mark the threshold of a critical interlude in the history of life. For the Cambrian is a period distinguished by the abrupt appearance of an astonishing array of multicelled animals—animals that are the ancestors of virtually all the creatures that now swim, fly and crawl through the visible world.

Indeed, while most people cling to the notion that evolution works its magic over millions of years, scientists are realizing that biological change often occurs in sudden fits and starts. And none of those fitful starts was more dramatic, more productive or more mysterious than the one that occurred shortly after Erwin's wormlike creature slithered through the primordial seas. All around the world, in layers of rock just slightly younger than that Erwin discovered, scientists have found the mineralized remains of organisms that represent the emergence of nearly every major branch in the zoological tree. Among them: bristle worms and roundworms, lamp shells and mollusks, sea cucumbers and jellyfish, not to mention an endless parade of arthropods, those spindly legged, hard-

ANOMALOCARIS

Some 515 million years ago, this looming 3-ft.-long predator prowled the seas, crushing prey in its circular jaw

Complex creatures with teeth and tentacles and claws and jaws materialized with the suddenness of apparitions

shelled ancient cousins of crabs and lobsters, spiders and flies. There are even occasional glimpses—in rock laid down not long after Erwin's Namibian sandstone—of small, ribbony swimmers with a rodlike spine that are unprepossessing progenitors of the chordate line, which leads to fish, to amphibians and eventually to humans.


DOUG ERWIN—NMNH

OTTOIA
This carnivorous worm, which grew up to 6 in. long, ambushed prey from its sea-floor burrow

Where did this extraordinary bestiary come from, and why did it emerge so quickly? In recent years, no question has stirred the imagination of more evolutionary experts, spawned more novel theories or spurred more far-flung expeditions. Life has occupied the planet for nearly 4 billion of its 4.5 billion years. But until about 600 million years ago, there were no organisms more complex than bacteria, multicelled algae and single-celled plankton. The first hint of biological ferment was a plethora of mysterious palm-shape, frondlike creatures that vanished as inexplicably as they appeared. Then, 543 million years ago, in the early Cambrian, within the span of no more than 10 million years, creatures with teeth and tentacles and claws and jaws materialized with the suddenness of apparitions. In a burst of creativity like nothing before or since, nature appears to have sketched out the blueprints for virtually the whole of the animal kingdom. This explosion of biological diversity is described by scientists as biology's Big Bang.

Over the decades, evolutionary theorists beginning with Charles Darwin have tried to argue that the appearance of multicelled animals during the Cambrian merely seemed sudden, and in fact had been preceded by a lengthy period of evolution for which the geological record was missing. But this explanation, while it patched over a hole in an otherwise masterly theory, now seems increasingly unsatisfactory. Since 1987, discoveries of major fossil beds in Greenland, in China, in Siberia, and now in Namibia have shown that the period of biological innovation occurred at virtually the same instant in geologic time all around the world.

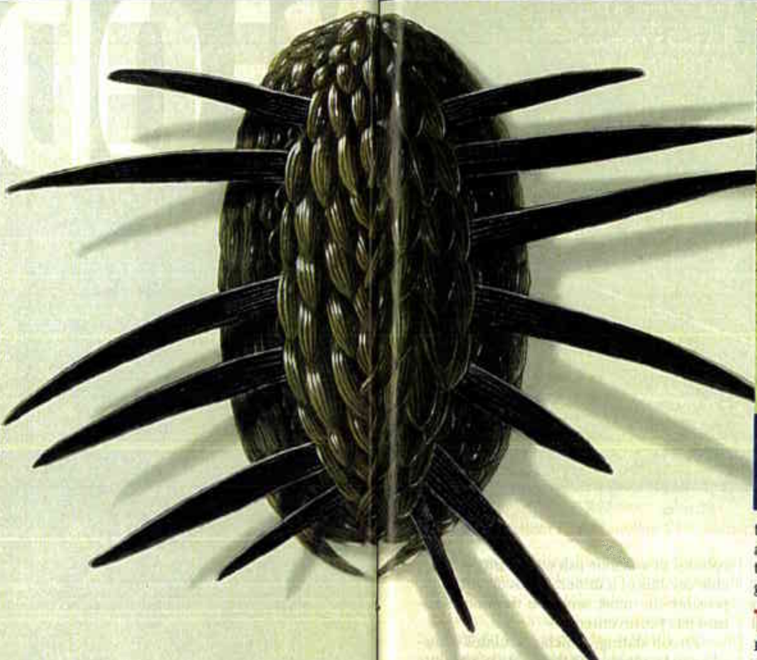
What could possibly have powered such a radical advance? Was it something in the organisms themselves or the environment in which they lived? Today an unprecedented effort to answer these questions is under way. Geologists and geochemists are reconstructing the Precambrian planet, looking for changes in the atmosphere and ocean that might have put evolution into sudden overdrive. Developmental biologists are teasing apart the genetic toolbox needed to assemble animals as disparate as worms and flies, mice and fish. And paleontologists are exploring deeper reaches of the fossil record, searching for organisms that might have primed the evolutionary pump. "We're getting data," says Harvard University paleontologist Andrew Knoll, "almost faster than we can digest it."

Every few weeks, it seems, a new piece of the puzzle falls into place. Just last month, in an article published by the journal *Nature*, an international team of scientists reported finding the exquisitely preserved remains of a 1-in.- to 2-in.-long animal that flourished in the Cambrian oceans 525 million years ago. From its flexible but sturdy spinal rod, the scientists deduced that this animal—dubbed *Yunnanozoon lividum*, after the Chinese province in which it was found—was a primitive chordate, the oldest ancestor yet discovered of the vertebrate branch of the animal kingdom, which includes *Homo sapiens*.

Even more tantalizing, paleontologists are gleaning insights into the enigmatic years that immediately preceded the Cambrian explosion. Until last spring, when John Grotzinger, a sedimentologist from M.I.T., led Erwin and two dozen other scientists on an expedition to the Namibian desert, this fateful period was obscured by a 20 million-year gap in the fossil record. But with the find in Namibia, as Grotzinger and three colleagues reported in the Oct. 27 issue of *Science*, the gap suddenly filled with complex life. In layer after layer of late Precambrian rock, heaved up in the rugged outcroppings the Namibians call *kopfs* (after the German word for "head"), Grotzinger's team has documented the existence of a flourishing biological community on the cusp of a startling transformation, a community in which small wormlike somethings, small shelly somethings—perhaps even large frondlike somethings—were in the process of crossing over a shadow line into uninhabited ecospace.

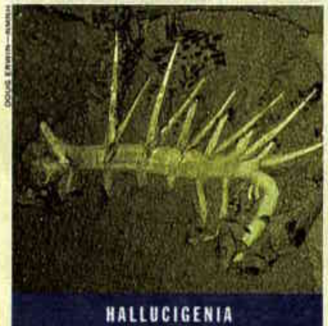
ILLUSTRATIONS BY KAM MAK—NATIONAL GEOGRAPHIC IMAGE COLLECTION

Here, then, are highlights from the tale that scientists are piecing together of a unique and dynamic time in the history of the earth, when continents were rifting apart, genetic programs were in flux, and tiny organisms in vast oceans dreamed of growing large.

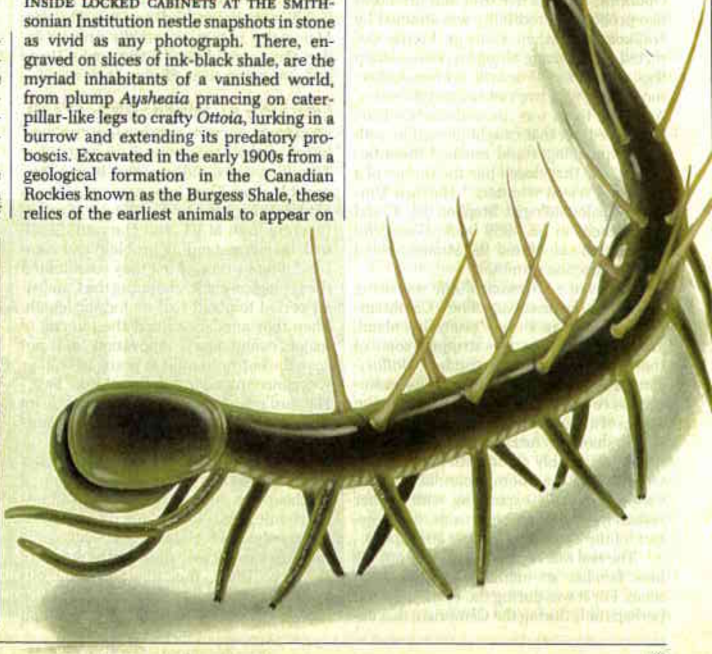



ERWIN—NMNH

WIWAXIA
As protection against attack, this sluglike creature grew scaly armor and bristled with needle-sharp spines


DOUG ERWIN—NMNH

HALLUCIGENIA
Scientists thought this ancient velvet worm tiptoed on its long, thin spikes—until they turned it right side up

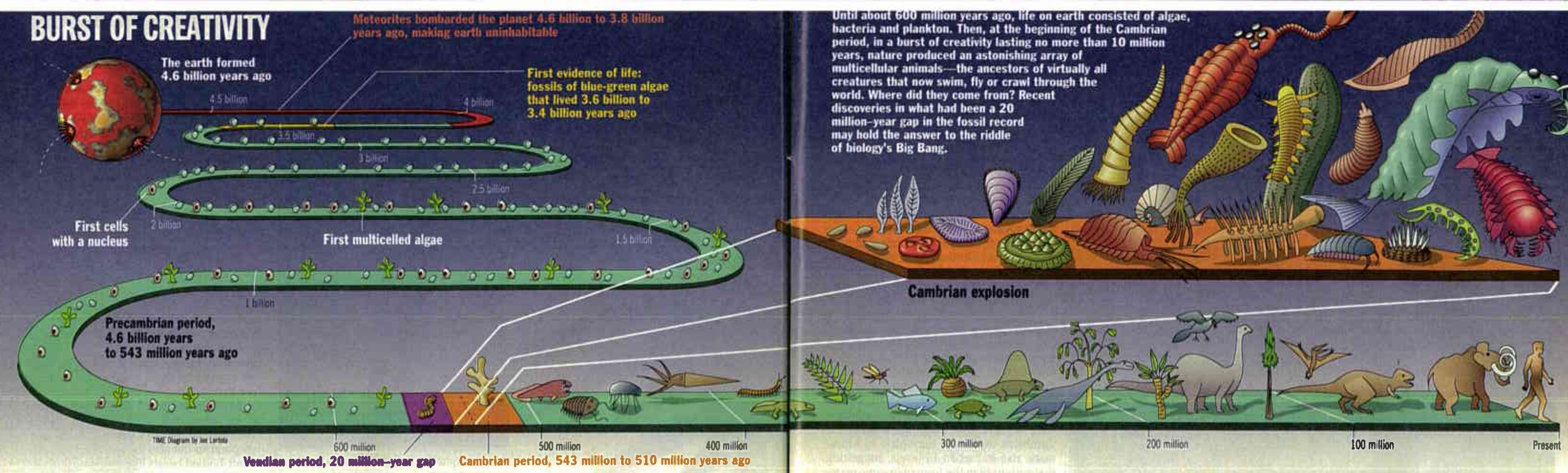


THE WEIRD WONDERS

INSIDE LOCKED CABINETS AT THE SMITHSONIAN Institution nestle snapshots in stone as vivid as any photograph. There, engraved on slices of ink-black shale, are the myriad inhabitants of a vanished world, from plump *Aysheaia* prancing on caterpillar-like legs to crafty *Ottoia*, lurking in a burrow and extending its predatory proboscis. Excavated in the early 1900s from a geological formation in the Canadian Rockies known as the Burgess Shale, these relics of the earliest animals to appear on earth are now revered as priceless treasures. Yet for half a century after their discovery, the Burgess Shale fossils attracted little scientific attention as researchers concentrated on creatures that were larger and easier to understand—like the dinosaurs that roamed the earth nearly 300 million years later.

Then, starting in the late 1960s, three paleontologists—Harry Whittington of the University of Cambridge in England and his two students, Derek Briggs and Simon Conway Morris—embarked on a methodical re-examination of the Burgess Shale fossils. Under bright lights and powerful microscopes, they coaxed fine-grain anatomical detail from the shale's stony secrets: the remains of small but substantial animals that were overtaken by a roaring underwater mudslide 515 million years ago and swept into water so deep and oxygen-free that the bacteria that should have decayed their tissues couldn't survive. Preserved were not just the hard-shelled creatures familiar to Darwin and his contemporaries but also the fossilized remains of soft-bodied beasts like *Aysheaia* and *Ottoia*. More astonishing still were remnants of delicate interior structures, like *Ottoia's* gut with its last, partly digested meal.

BURST OF CREATIVITY



Until about 600 million years ago, life on earth consisted of algae, bacteria and plankton. Then, at the beginning of the Cambrian period, in a burst of creativity lasting no more than 10 million years, nature produced an astonishing array of multicellular animals—the ancestors of virtually all creatures that now swim, fly or crawl through the world. Where did they come from? Recent discoveries in what had been a 20 million-year gap in the fossil record may hold the answer to the riddle of biology's Big Bang.

TIME Diagram by Joe Lertola

Soon, inspired reconstructions of the Cambrian bestiary began to create a stir at paleontological gatherings. Startled laughter greeted the unveiling of oddball *Opabinia*, with its five eyes and fire-hose-like proboscis. Credibility was strained by *Hallucigenia*, when Conway Morris depicted it as dancing along on needle-sharp legs, and also by *Wiwaxia*, a whimsical armored slug with two rows of upright scales. And then there was *Anomalocaris*, a fearsome predator that caught its victims with spiny appendages and crushed them between jaws that closed like the shutter of a camera. "Weird wonders," Harvard University paleontologist Stephen Jay Gould called them in his 1989 book, *Wonderful Life*, which celebrated the strangeness of the Burgess Shale animals.

But even as *Wonderful Life* was being published, the discovery of new Cambrian-era fossil beds in Sirius Passet, Greenland, and Yunnan, China, was stripping some of the weirdness from the wonders. *Hallucigenia's* impossibly pointed legs, for example, were unmasked as the upside-down spines of a prehistoric velvet worm. In similar fashion, *Wiwaxia*, some scientists think, is probably allied with living bristle worms. And the anomalocaridids—whose variety is rapidly expanding with further research—appear to be cousins, if not sisters, of the amazingly diverse arthropods.

The real marvel, says Conway Morris, is how familiar so many of these animals seem. For it was during the Cambrian (and perhaps only during the Cambrian) that nature invented the animal body plans that define the broad biological groupings known as phyla, which encompass everything from classes and orders to families, genera and species. For example, the chordate phylum includes mammals, birds and fish. The class Mammalia, in turn, covers the primate order, the hominid family, the genus *Homo* and our own species, *Homo sapiens*.

EVOLVING AT SUPERSONIC SPEED

SCIENTISTS USED TO THINK THAT THE EVOLUTION of phyla took place over a period of 75 million years, and even that seemed impossibly short. Then two years ago, a group of researchers led by Grotzinger, Samuel Bowring from M.I.T. and Harvard's Knoll took this long-standing problem and escalated it into a crisis. First they recalibrated the geological clock, chopping the Cambrian period to about half its former length. Then they announced that the interval of major evolutionary innovation did not span the entire 30 million years, but rather was concentrated in the first third. "Fast," Harvard's Gould observes, "is now a lot faster than we thought, and that's extraordinarily interesting."

What Knoll, Grotzinger and colleagues had done was travel to a remote region of northeastern Siberia where millenniums of relentless erosion had uncovered a dramatic ledger of rock more than half a mile thick. In ancient seabeds near the mouth of the Lena River, they spotted numerous small, shelly fossils characteristic of the early Cambrian. Even better, they found cobbles of volcanic ash containing minuscule crystals of a mineral known as zircon, possibly the most sensitive timepiece nature has yet invented.

Zircon dating, which calculates a fossil's age by measuring the relative amounts of uranium and lead within the crystals, had been whittling away at the Cambrian for some time. By 1990, for example, new dates obtained from early Cambrian sites around the world were telescoping the start of biology's Big Bang from 600 million years ago to less than 560 million years ago. Now, with information based on the lead content of zircons from Siberia, virtually everyone agrees that the Cambrian started almost exactly 543 million years ago and, even more startling, that all but one of the phyla in the fossil record appeared within the first 5 million to 10 million years. "We now know how fast fast is," grins Bowring. "And what I like to ask my biologist friends is, How fast can evolution get before they start feeling uncomfortable?"

FREAKS OR ANCESTORS?

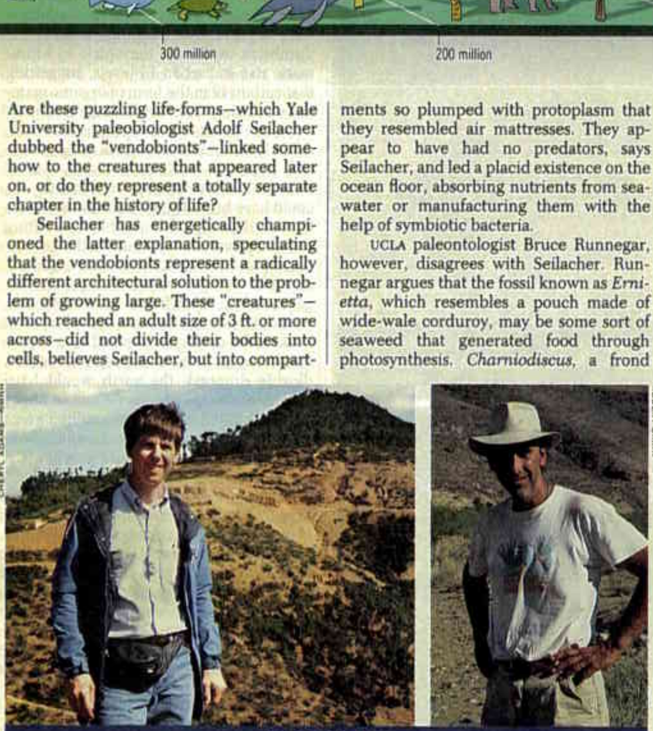
THE KEY TO THE CAMBRIAN EXPLOSION, researchers are now convinced, lies in the Vendian, the geological period that immediately preceded it. But because of the frustrating gap in the fossil record, efforts to explore this critical time interval have been hampered. For this reason, no one knows quite what to make of the singular frond-shape organisms that appeared tens of millions of years before the beginning of the Cambrian, then seemingly died out.

Are these puzzling life-forms—which Yale University paleobiologist Adolf Seilacher dubbed the "vendobionts"—linked somehow to the creatures that appeared later on, or do they represent a totally separate chapter in the history of life?

Seilacher has energetically championed the latter explanation, speculating that the vendobionts represent a radically different architectural solution to the problem of growing large. These "creatures"—which reached an adult size of 3 ft. or more across—did not divide their bodies into cells, believes Seilacher, but into compartments so plumped with protoplasm that they resembled air mattresses. They appear to have had no predators, says Seilacher, and led a placid existence on the ocean floor, absorbing nutrients from seawater or manufacturing them with the help of symbiotic bacteria.

UCLA paleontologist Bruce Runnegar, however, disagrees with Seilacher. Runnegar argues that the fossil known as *Ernietta*, which resembles a pouch made of wide-wale corduroy, may be some sort of seaweed that generated food through photosynthesis. *Charniodiscus*, a frond with a disklike base, he classifies as a colonial cnidarian, the phylum that includes jellyfish, sea anemones and sea pens. And *Dickinsonia*, which appears to have a clearly segmented body, Runnegar tentatively places in an ancestral group that later gave rise to roundworms and arthropods. The Cambrian explosion did not erupt out of the blue, argues Runnegar. "It's the continuation of a process that began long before."

The debate between Runnegar and Seilacher is about to get even more heated. For, as pictures that accompany the *Science* article reveal, researchers have returned from Namibia with hard evidence that a diverse community of organisms flourished in the oceans at the end of the Vendian, just before nature was gripped by creative frenzy. Runnegar, for instance, is currently studying the fossil of a puzzling conical creature that appears to be an early sponge. M.I.T.'s Beverly Saylor is sorting through sandstones that contain a menagerie of small, shelly things, some shaped like wine goblets, others like miniature curtain rods. And Guy Narbonne of Queen's University in Ontario, Canada, is trying to make sense of *Dickinsonia*-like creatures found just beneath the layer of rock where the Cambrian officially begins. What used to be a gap in the fossil record has turned out to be teeming with life, and this single, stunning insight into late-Precambrian ecology, believes Grotzinger, is bound to reframe the old argument over the vendobionts. For whether they are an-



CHERYL ADAMS—NMNH

ROBERT BRAIN

HOMO SAPIENS

Erwin, at a promising site in China, and Grotzinger, on location in Namibia, investigate ancient biological communities that were on the cusp of a startling transformation

As the genetic tool kit grew more intricate, life crossed a critical threshold. Boom: the Cambrian explosion

imal ancestors or evolutionary dead ends, says Grotzinger, *Dickinsonia* and its cousins can no longer be thought of as sideshow freaks. Along with the multitudes of small, shelly organisms and enigmatic burrowers that riddled the sea floor with tunnels and trails, the vendobionts have emerged as important clues to the Cambrian explosion. "We now know," says Grotzinger, "that evolution did not proceed in two unrelated pulses but in two pulses that beat together as one."

BREAKING THROUGH THE ALGAE

TO HUMAN EYES, THE WORLD ON THE EVE of the Cambrian explosion would have seemed an exceedingly hostile place. Tectonic forces unleashed huge earthquakes that broke continental land masses apart, then slammed them back together. Mountains the size of the Himalayas shot skyward, hurling avalanches of rock, sand and mud down their flanks. The climate was in turmoil. Great ice ages came and went as the chemistry of the atmosphere and oceans endured some of the most spectacular shifts in the planet's history. And in one way or another, says Knoll, these dramatic upheavals helped midwife complex animal life by infusing the primordial oceans with oxygen.

Without oxygen to aerate tissues and make vital structural components like collagen, notes Knoll, animals simply cannot grow large. But for most of earth's history, the production of oxygen through photosynthesis—the metabolic alchemy that allowed primordial algae to turn carbon dioxide, water and sunlight into energy—was almost perfectly balanced by oxygen-depleting processes, especially organic decay. Indeed, the vast populations of algae that smothered the Precambrian oceans generated tons of vegetative debris, and as bacteria decomposed this slimy detritus, they performed photosynthesis in reverse, consuming oxygen and releasing carbon dioxide, the greenhouse gas that traps heat and helps warm the planet.

For oxygen to rise, then, the planet's burden of decaying organic matter had to decline. And around 600 million years ago, that appears to be what happened. The change is reflected in the chemical composition of rocks like limestone, which incorporate two isotopes of carbon in proportion to their abundance in seawater—carbon 12, which is preferentially taken up by algae during photosynthesis, and carbon 13, its slightly heavier cousin. By sampling ancient limestones, Knoll and his colleagues have determined that the ratio of carbon 12 to carbon 13 remained stable for most of the Proterozoic Eon, a boggling expanse of time that stretched from 2.5 billion years ago to the end of the Vendian. But at the close of the Proterozoic, just prior to the Cambrian explosion, they pick up a dramatic rise in carbon 13 levels, suggesting that carbon 12 in the form of organic material was being removed from the oceans.

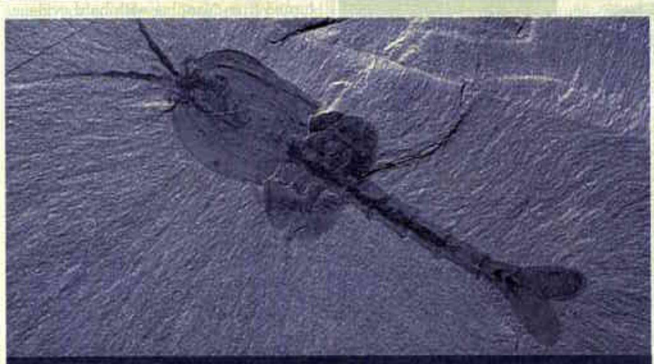
One mechanism, speculates Knoll, could have been erosion from steep mountain slopes. Over time, he notes, tons of sediment and rock that poured into the sea could have buried algal remains that fell to the sea floor. In addition, he says, rifting continents very likely changed the geometry of ocean basins so that water could not circulate as vigorously as before. The organic carbon that fell to the sea floor, then, would have stayed there, never cycling back to the ocean surface and into the atmosphere. As levels of atmospheric carbon dioxide dropped, the earth would have cooled. Sure enough, says Knoll, a major ice age ensued around 600 million years ago—yet another link in a complex chain that connects geological and geochemical events to a momentous advance in biology.

Biology also influenced geochemistry, says Indiana University biochemist John Hayes. In fact, in a paper published in *Nature* earlier this year, Hayes and his colleagues argue that guts, those simple conduits that take food in at one end and expel wastes at the other, may be the key to the Cambrian explosion. Their reasoning goes something like this: animals grazed on the algae, packaging the leftover organic material into fecal pellets. These pellets dropped to the ocean depths, depriving oxygen-depleting bacteria of their principal food source. The evidence? Organic lipids in ancient rocks, notes Hayes, underwent a striking change in carbon-isotope ratios around 550 million years ago.


DR. LARS RAMSKOLD—UNIVERSITY OF UPPSALA

YUNNANOZOON

This humble 2-in. chordate is the earliest known member of the line that led to humans


CHIP CLARK—NMNH

WAPTIA

This archaic crustacean is a progenitor of modern marine invertebrates like shrimp

Again, the change suggests that food sources rich in carbon 12, like algae, were being "express mailed" to the ocean floor.

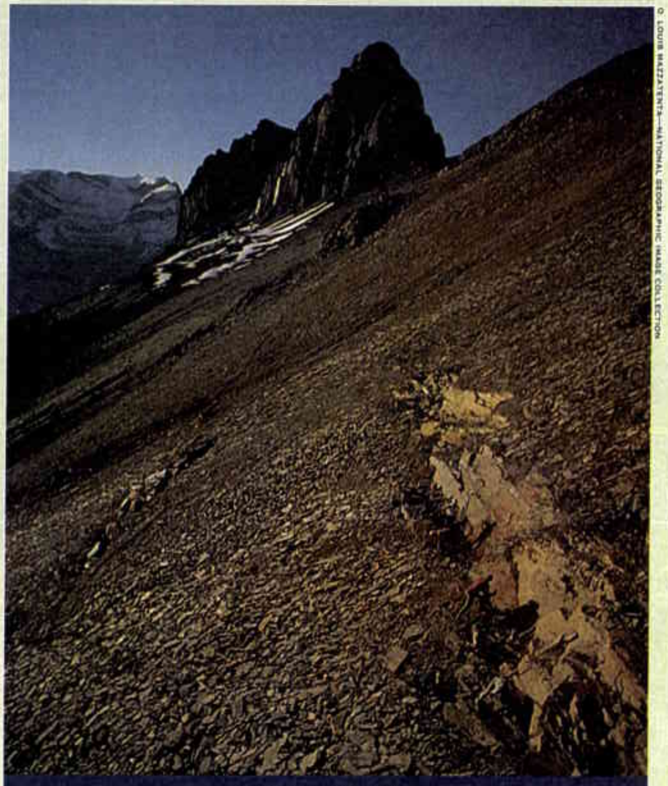
THE GENETIC TOOL KIT

THE ANIMALS THAT AERATED THE PRECAMbrian oceans could have resembled the wormlike something that left its meandering marks on the rock Erwin lugged back from Namibia. More advanced than a flatworm, which was not rigid enough to burrow through sand, this creature would have had a sturdy, fluid-filled body cavity. It would have had musculature capable of strong contractions. It probably had a heart, a well-defined head with an eye for sensing light and, last but not least, a gastrointestinal tract with an opening at each end. What kind of genetic machinery, Erwin wondered, did nature need in order to patch together such a creature?

Over the summer, Erwin pondered this problem with two paleontologist friends, David Jablonski of the University of Chicago and James Valentine of the University of California, Berkeley. Primitive multicelled organisms like jellyfish, they reasoned, have three so-called homeotic homeobox genes, or *Hox* genes, which serve as the master controllers of embryonic development. Flatworms have four, arthropods like fruit flies have eight, and the primitive chordate *Branchiostoma* (formerly known as *Amphioxus*) has 10. So around 550 million years ago, Erwin and the others believe, some wormlike creature expanded its *Hox* cluster, bringing the number of genes up to six. Then, "Boom!" shouts Jablonski. "At that point, perhaps, life crossed some sort of critical threshold." Result: the Cambrian explosion.

The proliferation of wildly varying body plans during the Cambrian, scientists reason, therefore must have something to do with *Hox* genes. But what? To find out, developmental biologist Sean Carroll's lab on the University of Wisconsin's Madison campus has begun importing tiny velvet worms that inhabit rotting logs in the dry forests of Australia. Blowing bubbles of spittle and waving their fat legs in the air, they look, he marvels, virtually identical to their Cambrian cousin *Aysheaia*, whose evocative portrait appears in the pages of the Burgess Shale. Soon Carroll hopes to answer a pivotal question: Is the genetic tool kit needed to construct a velvet worm smaller than the one the arthropods use?

Already Carroll suspects that the Cambrian explosion was powered by more than a simple expansion in the number of *Hox* genes. Far more important, he believes, were changes in the vast regulatory networks that link each *Hox* gene to hundreds of other genes. Think of these genes, suggests Carroll, as the chips that run a computer. The Cambrian explosion, then, may mark not the invention of new hardware, but rather the elaboration of new software that allowed existing genes to perform new tricks. Unusual-looking arthropods, for example, might be cobbled together through variations of the genetic software that codes for legs. "Arthropods," observes paleoentomologist Jarmila Kukalová-Peck of Canada's Carleton University, "are all legs"—including the "legs" that evolved into jaws, claws and even sex organs.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THE BURGESS SHALE

Scientists struck a rich lode of fossils in this outcropping in the Canadian Rockies

BEYOND DARWINISM

OF COURSE, UNDERSTANDING WHAT MADE the Cambrian explosion possible doesn't address the larger question of what made it happen so fast. Here scientists delicately slide across data-thin ice, suggesting scenarios that are based on intuition rather than solid evidence. One favorite is the so-called empty barrel, or open spaces, hypothesis, which compares the Cambrian organisms to homesteaders on the prairies. The biosphere in which the Cambrian explosion occurred, in other words, was like the American West, a huge tract of vacant property that suddenly opened up for settlement. After the initial land rush subsided, it became more and more difficult for naive newcomers to establish footholds.

Predation is another popular explanation. Once multicelled grazers appeared, say paleontologists, it was only a matter of time before multicelled predators evolved to eat them. And, right on cue, the first signs of predation appear in the fossil record exactly at the transition between the Vendian and the Cambrian, in the form of bore holes drilled through shelly organisms that resemble stacks of miniature ice-