The Early Evolution of Animals

Tiny fossils reveal that complex animal life is older than we thought—by at least as much as 50 million years

By David J. Bottjer

"THERE IS A BILATERIAN IN THAT TRUCK," Jun-Yuan Chen said as we watched the vehicle disappear around a bend in the road. Chen, a paleontologist at the Chinese Academy of Sciences in Nanjing, and I, along with Stephen Q. Dornbos, a colleague then at the University of Southern California, had just collected a truckload of black rocks from a 580-million- to 600-million-year-old deposit in Guizhou Province. Chen was sure they held something important.

We had come to Guizhou in 2002 to hunt for microscopic fossils of some of the earliest animals on earth. Specifically, we were hoping to find a bilaterian. The advent of bilateral symmetry—the mirror-image balance of limbs and organs—marks a critical step in the history of life. The first multicelled animals were not bilaterally symmetrical; they were asymmetrical aquatic blobs—sponges—that filtered food particles from currents they generated. Radially symmetrical

OLDEST FOSSIL ANIMAL with a bilateral body plan yet discovered, *Vernanimalcula* lived in the seas some 580 million to 600 million years ago. This reconstruction enlarges the creature to reveal its complexity; in life it was about the size of the period at the end of this sentence.

TWO DEPOSITS IN CHINA have preserved the remains of soft-bodied animals that provide new information about early evolution. In 2004 the author and his colleagues discovered the oldest known bilaterian animal in rocks collected from the 580-million- to 600-million-year-old Doushantuo Formation, near Weng'an. Significantly younger fossils from the approximately 525-million-year-old deposits in the vicinity of Chengjiang have expanded understanding of the Cambrian explosion.

aquatic creatures, the cnidarians, are slightly more complex; they have specialized stinging cells that can immobilize prey. Bilaterians constitute all the rest of us, from worms to human beings. During some stage in their life cycle, all display not only the crucial left-right balance but a multilayered body that typically has a mouth, gut and anus.

Until several years ago, consensus held that bilaterian animals first appeared in the fossil record about 555 million years ago, although the vast majority showed up somewhat later in a burst of innovation known as the Cambrian explosion, which began about 542 million years ago. The dearth of earlier fossils made it impossible to test ideas about what triggered the "explosion" or even to say for sure whether it was real or merely seemed so because earlier animals left few detectable traces of themselves. But research over the past half a dozen years—including ours in Guizhou Province—has changed the long-held view, suggesting that complex animals arose at least 50 million years earlier than the Cambrian explosion.

Molecular Clocks and Lagerstätten

MOLECULAR ANALYSIS, in particular a technique called the molecular clock, has been key in the new thinking about when the earliest animals arose. The clock idea is based on the supposition that some evolutionary changes occur at a regular rate. Over millions of years, for example, mutations may be incorporated in the DNA of genes at a steady rate. Differences in the DNA of organisms, then, can act as a "timepiece" for measuring the date at which two lineages split from a common ancestor, each going its separate way and accumulating its own distinctive mutations.

To estimate the timing of the origin of various major animal groups, Gregory Wray of Duke University and his colleagues used a molecular clock rate based on vertebrates (animals that have a backbone). Their results, published in 1996, postulated that bilaterians diverged from more primitive animals deep into the Precambrian era, as much as 1.2 billion years ago.

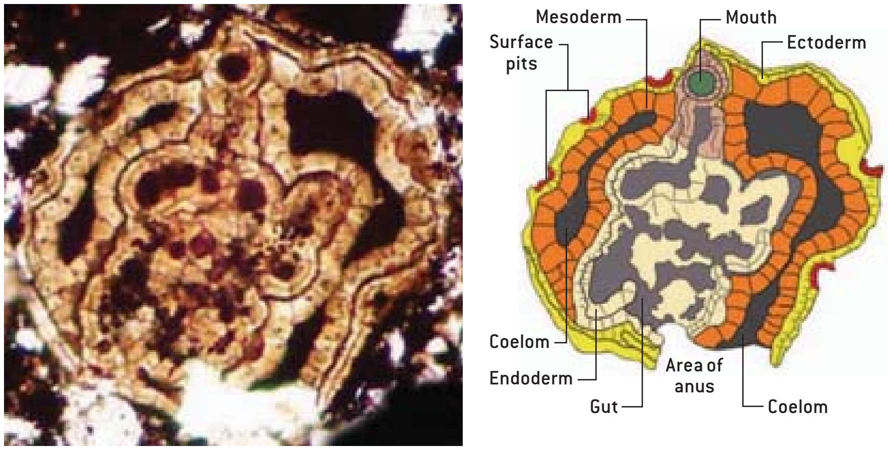
Follow-up studies using the molecular clock produced estimates for this split that varied significantly, ranging from as old as one billion years ago to as young as just before the Cambrian period. Such discrepancies naturally generated doubts about the technique, and a more recent study by Kevin Peterson of Dartmouth College and his colleagues addressed some of these concerns. In particular, they used a molecular clock rate derived from invertebrates, which is slower than the one based on vertebrates.

This investigation placed the last common ancestor of bilaterian animals at a much younger date, though still older than the Cambrian explosion, somewhere between 573 million and 656 million years ago. But even this date sparked controversy. It had become clear that only actual fossils would furnish incontrovertible evidence for the time at which bilaterians had emerged. This realization provided a big incentive for paleontologists to get out in the field and find fossils older than the Cambrian. I was among the scientists spurred to search for these elusive specimens.

Overview/*Older Than We Thought*

- The development of bilateral symmetry marks a critical step in the early evolution of animals.
- Genetic analysis has suggested that bilateral symmetry arose 573 million to 656 million years ago, but controversy clouds the date for several reasons. The most telling is that until recently the earliest known bilaterian fossils were dated to only 555 million years ago.
- Now the author and his colleagues have found supporting fossil evidence for the earlier date: microscopic creatures in Chinese deposits 580 million to 600 million years old.
- The minuscule fossils not only support an early date for the beginning of complex animal life but show that internal complexity evolved before large size did.

AMADEO BACHAR (*preceding pages*); ALISON KENDALL (*this page*)



BEST-PRESERVED SPECIMEN of *Vernanimalcula* is shown in the photomicrograph on the left. Diagnostic characteristics of a bilaterian are evident: a multilayered body with paired cavities called coeloms, a mouth and a gut. The drawing on the right highlights key features (the anus is not preserved in this specimen; its location is based on its placement in other specimens).

One huge problem with finding such animals is that they did not have hard skeletons that would mineralize and become fossils. So we must rely on uncovering the rare deposit that, because of the type of rock and the chemical processes involved, preserves intricate details of the remains. These deposits are called *lagerstätten,* a German word that means “lode places” or “mother lode.” A lagerstätte that preserves soft tissue is a spectacular rarity; we know of only several dozen scattered over the earth. One of the best known is the Solnhofen Limestone in Germany, where the 150-million-year-old feathered specimens of what is generally considered to be the earliest fossil bird, *Archaeopteryx,* are preserved. In British Columbia, an older deposit, the Burgess Shale, made famous by the writings of Stephen Jay Gould [see, for example, “The Evolution of Life on Earth,” SCIENTIFIC AMERICAN; October 1994], reveals a cornucopia of curious soft-bodied organisms from the ancient oceans of the Cambrian period.

A lagerstätte older than the Burgess Shale, in the Chengjiang area of China’s Yunnan Province, has yielded many important recent finds of soft-bodied organisms also characteristic of the Cambrian explosion. And, at several spots on the planet, the Ediacaran lagerstätten, named after the Ediacara Hills of Australia where the first example was found, harbor strange Precambrian soft-bodied fossils and animal burrows, including evidence for early bilaterians.

Amazingly, in 1998 two different groups of paleobiologists reported finding fossils with remarkable soft-tissue preservation in another Precambrian lagerstätte—the Doushantuo Formation in Guizhou Province of south China. This deposit contains tiny soft-bodied adult sponges and cnidarians as well as minuscule eggs and embryos. Much of the sediment in which they occur is composed of the mineral calcium phosphate (apatite), which has exquisitely replaced the original soft tissues of these fossils. The latest studies show that these rocks are older than the Ediacara biota, most likely 580 million to 600 million years old, and thus that the microfossils they contain lived 40 million to 55 million years before the Cambrian.

And So to China

THOSE OF US interested in the origin of animals quickly realized that the Doushantuo Formation might be the window through which we would glimpse early bilaterian life. So, in the autumn of 1999, a group of us joined together, at the urging of Eric Davidson, a molecular biologist at the California Institute of Technology, to study the Doushantuo microfossils. The team also included Chen and Chia-Wei Li, who were among the first investigators to report on eggs and embryos in the Doushantuo. Li, a professor at National Tsing Hua University, is an expert on biomineralization, and Chen has extensive experience studying early animal life through his pioneering work on the Lower Cambrian Chengjiang lagerstätte.

Our initial probes suggested that a relatively thin sedimentary layer, which is black in color, would be the most promising for finding a variety of microfossils. Other researchers at the site had applied acid to dissolve the rock matrix in the laboratory, revealing the tiny phosphatized fossils. Unfortunately, the acid dissolution technique was not successful with the layer of black rock that we had targeted. We therefore turned to a different approach: we collected great piles of this black rock and brought it back to Chen’s lab at the Early Life Research Center of the Nanjing Institute of Geology and Palaeontology in adjacent Yunnan Province. That is where our dump truck was headed when Chen made his bilaterian prediction.

Once back in Yunnan with our rocks, we sliced the samples into thousands of sections, so thin that they were translucent and, when mounted on glass slides, could be examined under a microscope. We made more than 10,000 of these slides, a gargantuan task that Chen and his technicians threw themselves into with optimism and energy. Painstaking analysis of the thousands of slides took several years and revealed myriad eggs and embryos; it confirmed the presence

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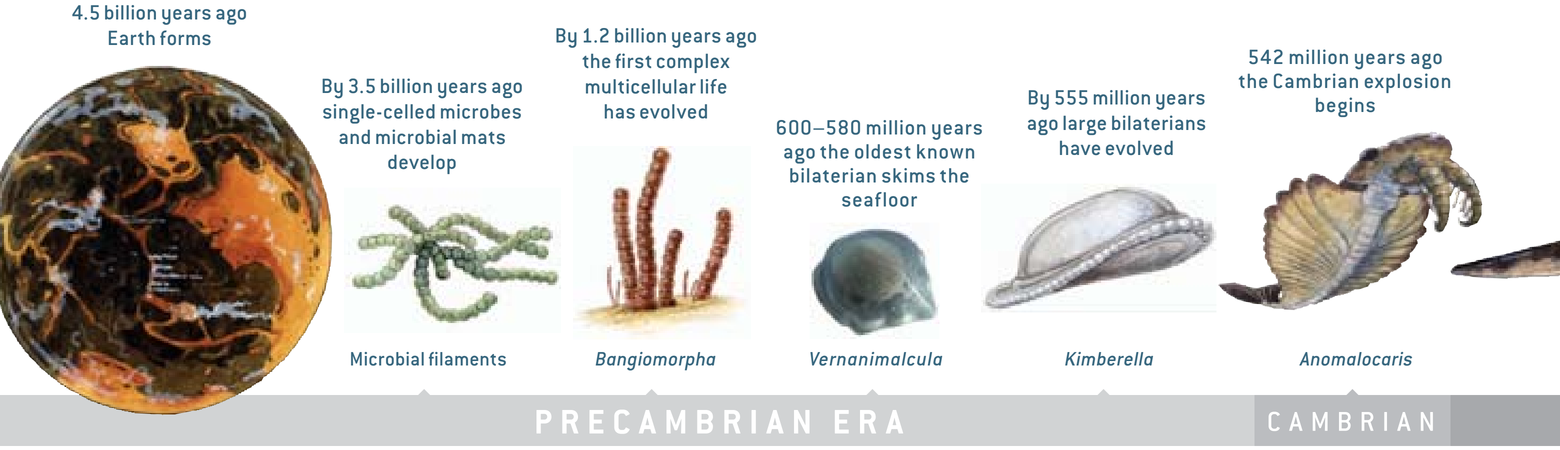
A Tiny Fossil's Place in History

The evolution of complex animal life was formerly thought to have started with a bang during the early Cambrian period, an event often referred to as the Cambrian explosion. The discovery in 2004 of the microscopic *Vernanimalcula* by the author and his colleagues pushes back the origins of complex animal life as much as 50 million years before the Cambrian.



of tiny adult sponges and cnidarians that had been reported previously.

But of course what we were really focused on finding was a bilaterian. Did our catch in the dump truck actually include one of these? In the summer of 2003 we began to zero in on one microfossil type whose complex morphological characteristics particularly intrigued us. Among the 10,000 slides, we were able to locate 10 examples of this type, and, early in 2004, after months of analysis, we came to the conclusion that this tiny organism displayed the basic features of a bilaterian. This was what we were looking for!

Ranging from 100 to 200 microns across, the width of several human hairs, these microscopic fossils are surprisingly complex and constitute almost a textbook example of a bilaterian, including the three major tissue layers (the endoderm, mesoderm and ectoderm familiar from high school biology texts), the

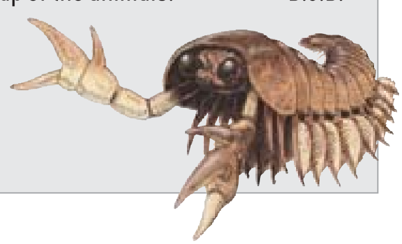
The Real Meaning of the Cambrian Explosion

The Cambrian explosion is generally thought of as a sudden increase in the types of bilaterian animals—those with a right-left balance of limbs and organs. But the story is more complicated, and more interesting, than that. Recent research has shown that a dramatic upsurge in interactions among animals played a large role in this increase in diversity.

First, animals began to alter the environment, and the new conditions created both opportunities and barriers for other denizens of the ancient world. For example, Precambrian animals that lived on the seafloor were adapted to moving about on cushiony microbial mats, which covered most of the ocean floor and had been part of the ecosystem since life originated. At the beginning of the Cambrian (which lasted from 542 million to 488 million years ago), however, evolutionary innovations enabled bilaterian animals to burrow vertically through sediment. The burrowing destroyed the ubiquitous mats and replaced them with a surface that was soupy and unstable. Some organisms, such as the helicoplacoids, small top-shaped animals that lived embedded in the seafloor, most likely became extinct as the sea bottom grew increasingly unstable. In contrast, other organisms reacted to this increase in bioturbation by evolving adaptations for living in the new environments.

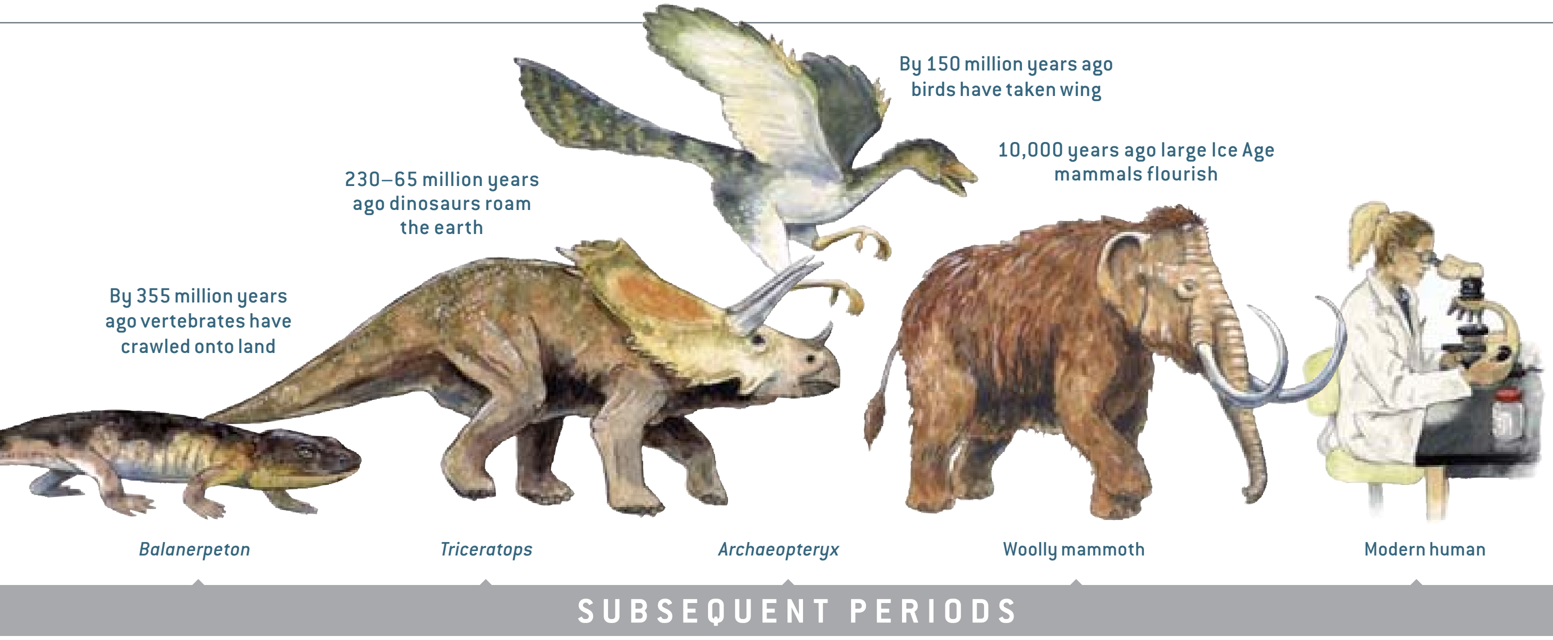
Second, the Early Cambrian marks the time when paleobiologists detect the first presence of bilaterian predators that had evolved to eat other animals. For example, Jun-Yuan Chen and Di-Ying Huang of the Chinese Academy of Sciences in Nanjing and others report several new types of predators from the Chengjiang lagerstätte in China. These include arthropods with strange frontal appendages for capturing prey (*below*), as well as ubiquitous burrowing worms that moved just below the seafloor and fed on other small animals.

These biological interactions played a strong role in the early evolution of animals. Yet as Charles Marshall of Harvard University has argued and as our findings support, the genetic tool kit and pattern-forming mechanisms characteristic of bilaterians had likely evolved by the time of the Cambrian explosion. Thus, the "explosion" of animal types was more accurately the exploitation of newly present conditions by animals that had already evolved the genetic tools to take advantage of these novel habitats rather than a fundamental change in the genetic makeup of the animals. —*D.J.B.*



EARLY PREDATOR, *Haikoucaris* (about four centimeters long)

AMADEO BACHAR



presence of a gut with a mouth and anus, and paired coeloms (body cavities) surrounding the gut. Oval-shaped and looking something like a minute gumdrop, the creature probably scooted along the seafloor to feed. At one end of the oval, the mouth sucked up microbes like a vacuum cleaner. Pits on either side of the mouth may have been sense organs.

We named our find *Vernanimalcula*, which means "small spring animal." The name refers to the long winter of "snowball Earth," when glaciers covered the planet [see "Snowball Earth," by Paul F. Hoffman and Daniel P. Schrag; SCIENTIFIC AMERICAN, January 2000]; the rocks holding *Vernanimalcula* are slightly above those marking the final glacial episode.

Legacy of a Small Spring Animal

BIOLOGICAL COMPLEXITY of the kind seen in *Vernanimalcula* implies a period of evolution that transpired long before the 580-million- to 600-million-year-old world in which the tiny animal lived. After all, it could not have gained that degree of symmetry and complexity all at once. We now need to find older lagerstätten that might hold clues to its ancestors.

We also need to move forward in time to try to puzzle out what happened to its descendants. What we know about life during the gap between *Vernanimalcula* and the creatures of the Cambrian explosion 40 million to 55 million years later comes primarily from studies of lagerstätten that contain the Ediacara biota—impressions and casts of soft-bodied organisms that were considerably larger than *Vernanimalcula*, ranging in size from centimeters to as much as a meter. New discoveries by Guy Narbonne of Queen's University in Ontario and his colleagues have confirmed the existence of these animals 575 million years ago; however, only in examples 555 million years old and younger do we find fossils that appear to represent bilaterians. Unlike the minuscule *Vernanimalcula*, these Ediacara bilaterians were macroscopic organisms, such as *Kimberella*, a soft-bodied sea dweller some 10 centimeters long that may have been an ancestor to the mollusks, animals that in today's seas include clams, snails and squid. Unfortunately, no Ediacaran deposits that we have located so far evince the unusual mineral setting essential for preserving microscopic creatures. To learn whether microscopic bilaterians existed alongside the larger Ediacara creatures we must find a fossil deposit of Ediacaran age that has preservation similar to that in the older Doushantuo Formation.

Although we cannot yet track the ancestors and descendants of *Vernanimalcula*, these tiny fossils have revealed a critical step in evolution: they show that bilaterians had the ability to make complex bodies before they could make large ones. Scientists are now speculating on what might have led to the eventual scaling-up of bodies. The most likely explanation is that a drastic rise in the amount of dissolved oxygen in seawater provided the impetus: more oxygen for respiration reduces constraints on size.

Vernanimalcula certainly gives paleontologists new inducements to go out and hunt for fossils of soft-bodied animals. We have a good deal left to learn, but the work so far has given substance to our earlier suspicion that complex animals have a much deeper root in time, suggesting that the Cambrian was less of an explosion and more of a flowering of animal life. SA

MORE TO EXPLORE

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