

Pushing Back the Origins of Animals

New fossils from China offer a first glimpse of familiar-looking animals before the Cambrian explosion 540 million years ago, and show how a full record of the dawn of animals might be assembled

The origins of the tremendous diversity of animals alive today—from sponges, tapeworms, snails, and spiders to sharks, bullfrogs, and humans—are hidden in the mists of time. If the fossil record is to be believed, these and other phyla—in fact, all the basic types of multicellular animals known today—burst on the scene in an evolutionary frenzy called the Cambrian explosion about 540 million years ago. Even paleontologists knew that that can't be the full story, however, for the Cambrian animals presumably had predecessors. But older rocks held few, if any, familiar-looking animals, and many researchers had lately resigned themselves to never finding any fossils of these small, squishy ancestors.

That left the question of when complex animal life arose and what it looked like to biologists, who in a flurry of recent work have been using the genes and embryos of living organisms to peer into the distant past (*Science*, 4 July 1997, p. 34). But with a pair of new findings, paleontologists have reentered the game. Their findings reveal a fossil history of animals stretching back tens of millions of years before the Cambrian explosion, opening up the dawn of animals to paleontological exploration.

In this issue of *Science* (p. 879) and in this week's *Nature*, two groups report that they have found microscopic fossils of animals and embryos exquisitely preserved in 570-million-year-old phosphorite rocks in south-central China. The new finds include submillimeter-sized marine sponges—the oldest known representatives of a living group of organisms—as well as ancient embryos that represent more advanced, bilateral animals. By showing that phosphate can fossilize tiny, fragile organisms from such ancient times, the finds have “really opened up a new way of looking for an older record of animals,” says paleontologist Andrew Knoll of Harvard University, one of the discoverers. “As paleontologists, we don't have to just sit in our armchairs and watch the debate.”

These first glimpses of that record suggest that the ancestors of today's kinds of animals were diverse and abundant well before the Cambrian explosion. The complexity of the fossils suggests that they must themselves have had even earlier, unknown ancestors and implies that the conservative dates once favored by some paleontologists for the origin of multicellular life—less than

600 million years ago—are too recent. The discoveries even raise hopes that fossils may one day help the molecular evolutionists settle their disputes about the dates of the first animals, which one camp now puts at a whopping 1.2 billion years ago and another at 670 million years.

Both new reports of early animals spring from the same source—a mine bored into the Doushantuo formation in central Guizhou province for its phosphate-rich rock used as fertilizer. Dated by correlation with deposits of known age to about 570 million years, give or take 20 million years, the Doushantuo had yielded remarkably well-preserved algae, according to published reports, but no animals. Last year, however, paleontologists Stefan Bengtson, of the Swedish Museum of Natural History in Stockholm, and Yue Zhao, of the Chinese Academy of Geological Sciences in Beijing, reported finding microscopic embryos in 530-million-year-old phosphate-rich rocks from China and Siberia (*Science*, 12 September 1997, p. 1645). That suggested that even older phosphate deposits might yield submillimeter-sized animals and embryos.

With that in mind, both groups independently realized that some of the “algae” from Doushantuo were actually animals and embryos. As they report in this issue, the team of cell biologists Chia-Wei Li and Tzu-En Hua of the National Tsing Hua University in Taiwan, and paleontologist Jun-Yuan Chen of the Nanjing Institute of Geology and Palaeontology in Nanjing, China, examined 150- to 750-micrometer spheroids and recognized sponges, among the most primitive of living multicellular animals. “I usually regard myself as a skeptic,” says Bengtson, but he finds the sponge argument “very convincing.” Not only are there abundant spicules—a sponge's sili-

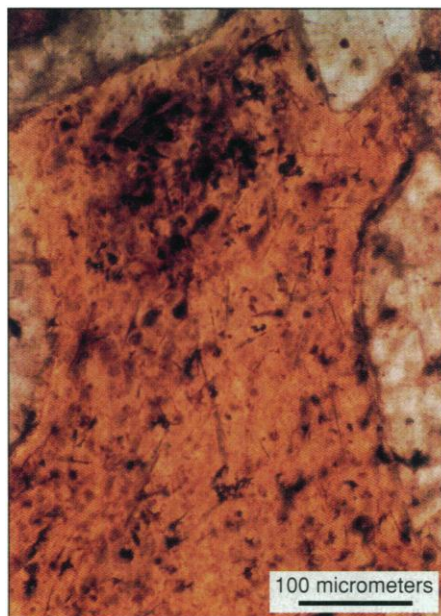
ceous, needlelike structural elements—but some spicules are still attached to the fossilized cells that produced them. These are the oldest known representatives of a living phylum, says Li, whose group also reports identifying sponge embryos and—tantalizingly—“many different metazoan taxa other than sponges.”

The other group, consisting of paleontologists Shuhai Xiao of Harvard, Yun Zhang of Beijing University, and Knoll, also reports a

range of microscopic embryos in the *Nature* paper. Bengtson finds their interpretation of these roughly 500-micrometer spheroidal bodies as embryos containing one, two, four, eight, and more cells “very reasonable,” because the fossils are the same size no matter how many cells they contain. That's just the way early-stage embryos behave as their constant volume is divided and redivided; in contrast, algal cells tend to be similar in size, so the girth of a clump of algae would depend on the number of cells in the cluster. The team reports

that in four-cell embryos, the cells are arranged in a strict tetrahedron—a hallmark of animals that have bilateral symmetry and are therefore much more advanced than sponges.

Paleontologists had hardly dared hope to find embryos in the fossil record, as that requires exquisite preservation of soft tissue. These Doushantuo fossils “yet again show the potential of phosphatization as a means of preserving incredible detail,” says paleontologist Simon Conway Morris of Cambridge University. Just how phosphate manages to freeze even the tiniest details of soft tissues is unclear, says Knoll. When the Doushantuo formed, large amounts of dissolved phosphate were apparently delivered to a shallow sea floor covered by low-oxygen waters, a place where small creatures could be preserved within days of their deaths. Similar conditions have prevailed in a range of times and places



Not for the bathtub. This submillimeter sponge with needlelike spicules is 570 million years old.

throughout the geologic record, and that is raising hopes that this glimpse of Precambrian animals will soon turn into a panorama. "Both the *Nature* and *Science* papers show we can map out early animal evolution," says Bengtson. "There are other phosphorites that we should go back to and look at with our new eyes. It's a new world waiting."

"The big question," says Conway Morris, "is how much farther back this will go." It might go quite a ways. Developmental biologist Eric Davidson of the California Institute of Technology in Pasadena and his colleagues have suggested that life might have spent many tens, even hundreds, of millions of years as tiny, simple assemblages of cells—"squishy little larvalike things"—that were more sophisticated than sponges but were prevented from evolving into the larger forms preserved at the Cambrian explosion by a developmental barrier (*Science*, 24 November 1995, p. 1300). Davidson's team suggested that paleontologists would therefore miss all the early action, but the new fossils raise the possibility that such tiny life-forms may be in the record after all, says Knoll. Davidson agrees that this is the most direct fossil evidence yet for an extended history for his larvalike animals.

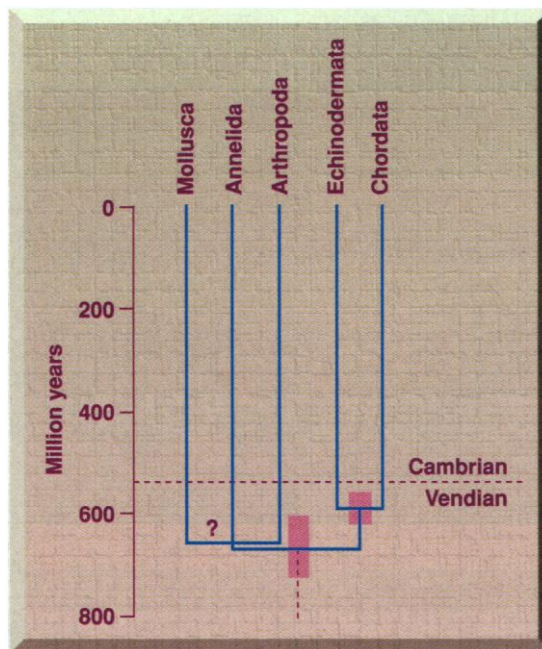
Meanwhile, other biologists have also been theorizing about the origins of animals, and some have been pushing for very early dates for these life-forms. In 1996, for example, molecular evolutionist Gregory Wray and colleagues at the State University of New York, Stony Brook, analyzed the sequences and evolution of eight genes across the living animal phyla (*Science*, 25 October 1996, p. 568).

Assuming that mutation rates were constant, they used the amount of gene-sequence difference among various organisms to calculate how long ago the groups split. They concluded that a deep division among these animals—between the mollusks, annelid worms, and arthropods (called the protostomes) on one hand and the echinoderms and chordates (called the deuterostomes) on the other—happened a whopping 1.2 billion years ago. The split between bilaterally symmetric animals (like people) and radially symmetric ones (like jellyfish) would have been even earlier.

But other molecular evolutionists aren't convinced. In the 25 January issue of the *Proceedings of the National Academy of Sciences*, Francisco Ayala of Pennsylvania State University (PSU) in University Park, statistical analyst Andrey Rzhetsky of Columbia University, and Ayala's father—evolutionary biologist Francisco José Ayala of the University of California, Irvine—reanalyze the

gene data used by Wray and his colleagues. They use rates for 12 additional genes and throw out data from genes whose rates of evolution appeared to change over time. Their result: The protostome/deuterostome split occurred 670 million years ago, give or take 60 million years (see diagram).

That's at least drawing closer to dates from the fossil record, says evolutionary biologist Charles Marshall of the University of California, Los Angeles. "Seven hundred million years is a pretty long way out" for life to have existed without leaving a trace, he says. "But [at least] it's not a billion." The numbers from genetic studies may eventually converge, for more studies from more genes



Looking back. The latest molecular study dates a key branch point in the tree of life to about 670 million years ago.

are on the way. But for now, their estimates for the protostome/deuterostome split range from 670 million to 1500 million years, according to a limited survey by *Science*. As molecular evolutionist Xun Gu of PSU notes, with some understatement, "This problem needs more data."

The new paleontological findings show that the additional data won't be coming from genes alone. Knoll predicts that "over the next few years, you are going to see people finding comparable fossils in yet older rocks." And finding whole animals—perhaps even the common ancestor of vertebrates and invertebrates at the root of the animal family tree—is a real possibility. Paleontologists may be able to test some of biologists' ideas on what the ancestral animal looked like, says Doug Erwin of the National Museum of Natural History in Washington, D.C., and "that's pretty exciting."

—Richard A. Kerr

MATHEMATICS

Proving a Link Between Logic And Origami

BALTIMORE—If you have ever tried to fold an origami boat or swan, you know it's not as easy as the step-by-step instructions suggest. But try doing it with just an unfolded square of paper and nothing but the crease lines. Even the most dedicated amateur origamist might give up in frustration when faced with the challenge of making the folds in the proper order. Predicting the properties of the finished origami model is still more daunting: It involves solving a problem that's as hard as anything known to computer scientists.

A pair of computer scientists has now shown that a well-known origami problem called the flat-folding problem belongs to a class of tasks that mathematicians call NP-complete: problems so difficult that each contains the key to solving—or being unable to solve—all the rest. (The initials "NP" stand for "nondeterministic polynomial time," which is computer science jargon for "may take an awfully long time unless you make a lucky guess.") The problem, predicting whether an origami model can be folded flat between the pages of a book without creating any new creases or otherwise damaging the model, has long tantalized the small community that studies the mathematics underlying origami. Now Barry Hayes, a computer scientist at the Mountain View, California, software firm Placeware Inc., and Marshall Bern of Xerox's Palo Alto Research Center have shown that this question is equivalent to a famous "hard" problem in computer science known as not-all-true 3-SAT.

The proof, which Hayes presented at a meeting here* in a session devoted to mathematical aspects of origami, is "a capstone of the type of research that has been emerging in origami mathematics," says Thomas Hull, a mathematician at Merrimack College in Andover, Massachusetts, who organized the session. Even though Hayes and Bern's proof is of purely theoretical interest, Hull says he is "delighted by the result," because the glimpse of a connection between paper sculpture and a much-studied problem in computer science may help bring other researchers into the fold.

The computer-science problem, not-all-true 3-SAT, involves determining whether a given logical expression, created by stringing together simple, three-term clauses, can be sat-

* Annual meetings of the American Mathematical Society and the Mathematical Association of America, 7–10 January.