PALEONTOLOGY

Evolution's Big Bang Gets Even More Explosive

Life on Earth was a slow starter. Single-celled organisms made their debut in the geologic record nearly 3.5 billion years ago, but until less than 600 million years ago, early in the Cambrian Period, evolution dragged. Then something clicked, and animals burst into a multimillion-year frenzy of evolutionary innovation like nothing ever seen before or since. "The lid was off; evolution was going full tilt. Never again in the history of marine life do we see so many phyla, classes, or orders appearing so rapidly," says paleontologist Jack Sepkoski of the University of Chicago. "Virtually every phylum of [marine invertebrate] animals comes in, plus things that can't be related to modern forms. They're the fastest rates of evolution we ever see." And now this "Cambrian explosion" of life has gotten even more spectacular.

On page 1293 of this issue of *Science*, geochronologist Samuel Bowring of the Massachusetts Institute of Technology (MIT) and his colleagues report that two lumps of volcanic rock from Siberia have yielded a new, more recent date for the beginning of the explosion, shrinking its duration to a mere 5 million to 10 million years—less than a third as long as paleontologists had traditionally assumed. "This Big Bang in animal evolution happened faster than we imagined," says Sepkoski. And that means paleontologists will have to reconsider past explanations of what caused the Cambrian explosion and possibly come up with new ones. They had invoked such mechanisms as changes in atmospheric composition, sudden shifts of continents, and new features of the animals' own physiology. But whether those explanations will hold up in light of the new date is anyone's guess.

Until now, almost every wall-chart of the geologic time scale put the beginning of the Cambrian explosion at 570 million years ago and its end 20 million to 40 million years or more later. But those dates were never really firm. The order of events was clear enough from the sequence of fossils laid down stratum by stratum: Simple, mostly unskeletonized animals appear in the Precambrian, before 600 million years ago, then give way in the Cambrian explosion to arthropods such as trilobites, shelled mollusks, starfish-like echinoderms, and bizarre creatures such as the aptly named *Hallucigenia*. The absolute timing and therefore the duration of events could not be measured accurately, however.

The problem was that Cambrian fossils and most of the sedimentary rock in which they are found can't be given an absolute age, since they lack sufficient amounts of the radioactive elements needed for dating. Volcanic rock, which often does have the right elements, is scarce in Cambrian strata. What dates were available were suspect because the existing techniques relied on elements such as rubidium that could be leached out of minerals over hundreds of millions of years.

SMITHSONIAN

Progeny of the explosion. The burst of evolutionary innovation about 530 million years ago led to diverse new creatures, including *Hallucigenia*.

Beginning in the 1980s however, refined isotopic dating methods based on the decay of uranium to lead were beginning to narrow the uncertainties. Researchers had more confidence in these techniques because the key uranium and lead isotopes can be tightly locked in crystals of zircon, a mineral commonly found in volcanic rocks. And because each sample contains two different clocks—two radioactive isotopes of uranium and their lead decay products—investigators can double-check how well the sample has retained the key elements and even correct for losses.

Last year geochronologist William Compston of the Australian National University in Canberra and his colleagues measured uranium and lead isotopes in zircons from Cambrian strata in Morocco. The uranium-lead dating revealed that the explosion had ended about 525 million years ago, tens of millions of years later than many time scales had assumed. If the 570-million-year age for the explosion's beginning were correct, that would have implied a longer evolutionary frenzy than was thought. But Bowring and colleagues have now used a different version of uranium-lead dating to determine a dramatically younger age for the beginning of the Cambrian explosion—533 million years or less. That result squeezes the explosion down to a few million years.

The discovery is one of the fringe benefits of the end of the cold war. Geologist John Grotzinger of MIT found the crucial samples—the cobble-sized remains of a volcanic eruption laid down when the evolutionary explosion began—in Siberia while doing field work last summer with Peter Kolosov of the Yakutian Geoscience Center in Yakutsk. The site on the Arctic coastline where they found the rock had been closed to foreigners because of its early-warning defense radars, and on geologic maps the exposed Cambrian layer had been labeled as simply a "conglomerate," giving no hint that it contained datable volcanic rocks. After separating zircons from two of their samples, Bowring and Clark Isachson of MIT measured the uranium and lead isotope content to get the crucial date.

With the Cambrian explosion now confined to a mere 5- to 10-million-year interval around 530 million years ago, paleontologists will be revisiting earlier notions about what could have set off such an intense burst of evolutionary creativity. An often-proposed idea is that multicellular animals couldn't proliferate until atmospheric oxygen, which had been rising gradually, crossed a threshold. Until then, the theory goes, organisms had to be small and simple because there was not enough oxygen around to support the metabolic machinery of multicellular animals. The problem with that idea is timing: The first sizable multicellular animals appear in the fossil record roughly 575 million years ago, well before the beginning of the Cambrian explosion, says evolutionary biologist Andrew Knoll of Harvard University, a co-author of the *Science* paper.

Rather than a dearth of oxygen, some researchers have suggested that maybe it was animals' sheer simplicity that held them back. Until animals reached a certain level of physiological and anatomical complexity, this reasoning goes, they could not expand into many ecological niches left empty until then. Once animals achieved the complexity of modern worms, says Sepkoski, "they exploded into these ecological arenas, exploiting new resources, including each other." Indeed, some paleontologists view the sudden profusion of protective shells and armor plating during the Cambrian explosion as a response to the new-found ability of animals to prey on one another.

Not content to leave the explanation to biologists, paleomagnetician Joseph Kirschvink of the California Institute of Technology has proposed a tectonic driving force for the Cambrian explosion. He sees evidence in the paleomagnetic and geologic records for a thorough reorganization of Earth's crustal motions about the time of the explosion. That redistribution of mass in turn seems to have caused Earth's outer shell of tectonic plates to slip as a unit around the planet's insides, Kirschvink says, like the crust of a hot roasted marshmallow. The geologically sudden shifts of latitude and climate that resulted could have driven an evolutionary leap. Whether it was an arms race among emerging new predators and prey or a slip-sliding Earth, the cause of the Cambrian explosion—when it's finally pinned down—is likely to be as startling as the event itself.

–Richard A. Kerr

MICROSCOPY

Light Microscopes Get a Sharper Look

In modern biology, light microscopes have largely gone by the board, replaced by elaborate imaging machines that depend on electrons, or positrons, or other exotic means of making images rather than plain old light. But light microscopy could be making a comeback. A team of Berkeley scientists has added a laser to an optical microscope, bounced the light off samples, and produced images with such remarkable vertical resolution that they might interest a new generation of researchers in the virtues of light.

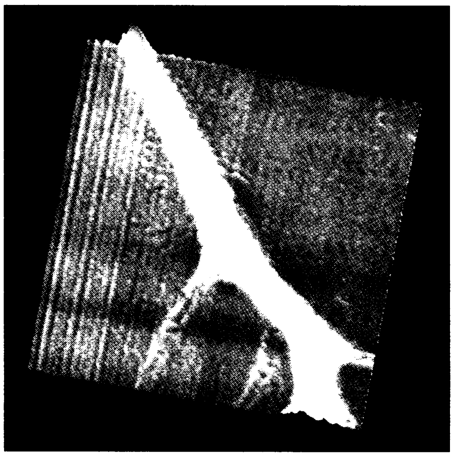
The new instrument, the laser feedback microscope (LFM), was introduced at the annual meeting of the Microscopy Society of America (MSA) in Cincinnati last month by Berkeley biophysicist Alan Bearden, who, with his then-graduate student, Michael O'Neill, and several other colleagues, invented the device. The LFM's superb vertical resolution—capable of measuring a mere 100 Angstroms, or 10 nanometers—met with high approval. "That's very sensitive to depth, something the scanning electron microscope can't detect," says microscopist Steven Pennycook of Oak Ridge National Labs in Tennessee. "It's great for measuring precise heights along the surface of a sample." The horizontal resolution of the images, however, leaves the machine's inventors unsatisfied—and standard microscopy theory holds that it won't be easy to improve.

Nevertheless, unlike electron microscopes, the LFM can examine live cells or other objects without damaging them. As an added bonus, the machine is relatively inexpensive, with an estimated cost of \$50,000—compared to over \$100,000 for a typical scanning electron microscope. The University of California is currently looking for licensing partners to build the machines.

That imaging systems based on light are making a comeback is something of a surprise, since optical microscopes fell into disfavor years ago because they weren't up to analyzing the minute intracellular structures researchers are interested in. The resolution of an image is inversely proportional to the wavelength used to make it, and the wavelengths of light were too long, resulting in fuzzy pictures. But electron microscopes, though they could give detail on structures as small as viruses, have drawbacks of their own. They require carefully prepared, vacuum-packed samples, eliminating the chance to examine a live cell. Moreover, the hail of electrons they produce can damage delicate samples.

The LFM, in contrast, is an optical instrument based on confocal microscopy—a microscope that bounces light off a single point and back through a tiny pinhole, thus getting improved focus on a single point at a time. This technique brought the optical microscope resolution up to 5000 Angstroms. But the Berkeley team realized they could do better—by changing the way they used the light.

Instead of using light to make images—limited, of course, by that irreducible wavelength—they use laser light as a measuring stick to probe the height differences between adjacent points along the surface of a sample. The process works like this: The microscope sends a laser beam through a pinhole to a precise point on a sample, where it then reflects back up through the hole. Light waves from the original beam and its reflection come together—either becoming brighter, canceling each other out, or a result in between, depending on how far the reflected beam has traveled. The degree of brightness thus indicates the height of the point on the sample. The microscope repeats this process on the next point, and then the next one, eventually feeding all these coordinates into a computer, which creates a precise drawing of every hill and valley on the sample.



Focus like a laser. This image of a chick embryo neuron, originally 40 × 40 micrometers, was produced by a laser feedback microscope.

The direct reflected light the LFM analyzes is a tiny amount—often as little as one-millionth of the original beam. That's why using the laser beam, instead of regular light, is so important. Since the makeup of a laser beam is so specific—comprised of only one wavelength of light—it can only interact with itself, so extra background light can't affect its brightness, explains Berkeley graduate student Terry Wong, who built the most recent version of the LFM. Letting a laser beam bounce back into itself had been considered taboo by most physicists who use lasers, since the beam's brightness can vascillate wildly with the tiniest impetus. But the Berkeley team realized those changes were precisely the variations in brightness that they were looking for.

Once they fitted a laser to their microscope, the team was amazed at the resulting detail. One hundred Angstroms high is only $\frac{1}{60}$ of a light wavelength—and 30 times better than a standard electron microscope. The new instrument is no slouch in the horizontal plane, either. The microscope can reveal details 200 nanometers—which is only slightly larger than those seen by a scanning electron microscope and twice as good as other confocal light microscopes. And, of course, the LFM doesn't damage what it looks at.

As the resolution has gone up, the price has gone down. "There's a cheapo laser and a photodetector and a couple of lenses and a computer and that's it," says Bearden. The relatively low price has already made the device attractive enough so that Ultrapointe Corp. of San Jose, California, has purchased an exclusive license for semiconductor applications.

While the microscope users in Cincinnati seemed quite impressed with the LFM, Bearden isn't satisfied with the horizontal resolution. Some researchers, however, think he doesn't have much choice, since standard microscopy theory holds that it's not possible to improve it. "Examining the latitude is always going to be limited by the wavelength of light," says Pennycook, simply because one can't manipulate the width of a beam the way that you can manipulate the distance it travels. But Bearden is convinced that he can circumvent what he says are misunderstood theories. And while it looks like a long shot, he's been pretty creative so far.

–Karen Fox