Shape of Life

The Cambrian Explosion

A Big Bang in the Evolution of Animals

Very suddenly, and at about the same horizon the world over, life showed up in the rocks with a bang. For most of Earth's early history, there simply was no fossil record. Only recently have we come to discover otherwise: Life is virtually as old as the planet itself, and even the most ancient sedimentary rocks have yielded fossilized remains of primitive forms of life.

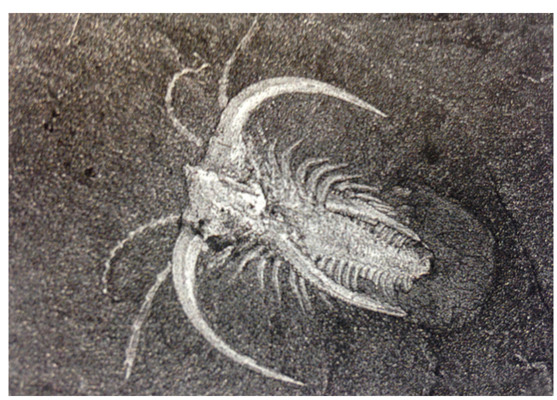
NILES ELDREDGE, *LIFE PULSE, EPISODES FROM THE STORY OF THE FOSSIL RECORD*

Our home planet coalesced into a sphere about four-and-a-half-billion years ago, acquired water and carbon about four billion years ago, and less than a billion years later, according to microscopic fossils, organic cells began to show up in that inert matter. Single-celled life had begun. Single cells dominated life on the planet for billions of years before multicellular animals appeared.

Fossils from 635,000 million years ago reveal fats that today are only produced by sponges. These biomarkers may be the earliest evidence of multi-cellular animals. Soon after we can see the shadowy impressions of more complex fans and jellies and things with no names that show that animal life was in an experimental phase (called the Ediacran period). Then suddenly, in the relatively short span of about twenty million years (given the usual pace of geologic time), life exploded in a radiation of abundance and diversity that contained the body plans of almost all the animals we know today.

In the first decade of the twentieth century, we found fossils that confirm this one-of-a-kind explosion of life, and as is the case with all great moments in science, there is a story. Actually, there are several versions, but in the one told most often around the campfires of paleontologists, the stumbling horse of the wife of a fossil hunter named Charles Walcott led to the discovery of a 530 million-year-old deposit of sediment that has come to be known as the Burgess Shale. Maybe it was the luck of Helena Walcott's foul-footed mount, maybe not, but in late August 1909, in the rocks kicked off a cliff face on a ridge between Mt. Wapta and Mt. Burgess, her husband found and retrieved not only some new notes in the fossil record, but a soaring crescendo that would forever change the way we listen to the past.

The Burgess Shale contains the fossils not just of a diversity of animals with hard skeletons, but also of a suite of rare, soft-bodied forms that died suddenly when a turbulent mudslide carried an entire community of animals to the bottom of a submarine cliff and into a basin with little available oxygen. Without oxygen, the bodies never decomposed, so over time they were covered by sediment that turned to rock, creating exquisitely detailed fossils, shadows of the ancient past in what became dark Cambrian shale. Since Walcott's discovery of the Burgess Shale fossils, other paleontologists working around the world, most notably in China and Utah, have found other fossils from the same period, which means that the Cambrian Explosion occurred simultaneously all over the globe.

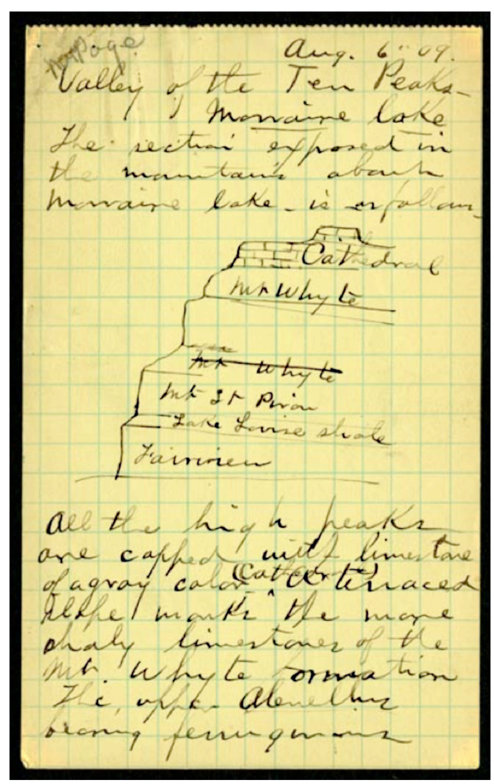


Burgess Shale arthropod fossils: *Moalria spinifera (top)* and the Lace Crab *Marrella splendens*, the most abundant fossil (bottom).

When Charles Walcott discovered the fossils of the Burgess Shale, he was arguably the most powerful and influential scientist in America. Secretary of the Smithsonian Institution, and a Victorian gentleman, he carried the mission of discovery like a battle flag. He was also the director of the U.S. Geological Survey, president of both the National Academy of Sciences and the American Association for the Advancement of Science, and custodian of America's forest reserves. His trip to the Burgess Shale was one of the annual family outings that remain popular among paleontologists, and he had gone to the Rockies hoping to find trilobites and their arthropod relatives.

Walcott's Quarry at the Burgess shale B.C., 1924.

Walcott shipped his specimens back to the Smithsonian, set about classifying them and soon declared most of them to be related to modern groups of animals, especially arthropods. Though he was way off the mark in many of the specifics of his identifications, he did the best he could, given the science and technology of his time. The possibility that the fossils of the Burgess Shale represented a sudden radiation of dozens of the modern animal body plans flew in the face of the current understanding of the natural laws of evolution pioneered by Charles Darwin and the underpinning for all investigation of the animals of the past at that time. Evolution seemed until then to progress at a steady rate. Gradually. The possibility that a sudden burst of speciation could occur was not then available to logic. (Even today, scientists debate the amount of time over which the Cambrian radiation occurred.) The fossils of the Burgess Shale were weird and fascinating, but they reposed in boxes in the Smithsonian and other paleontological collections for another sixty years before their true meaning was known.



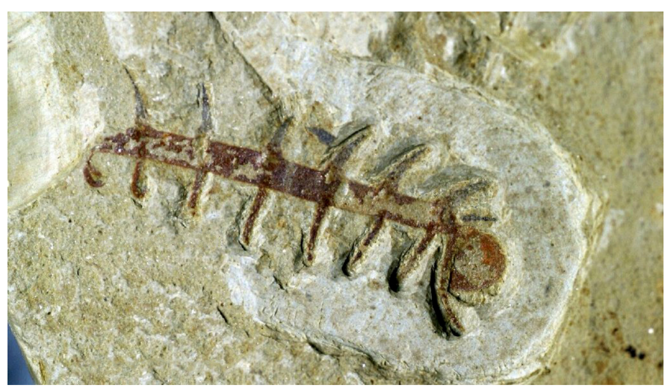
Field notes of Charles D. Walcott, August 6, 1909, describing of geological formation of Moraine Lake at Valley of the Ten Peaks, Banff National Park, Canada. SOURCE: From the Smithsonian the National Museum of Natural History.

Piecing Together Burgess Shale Fossils

All those scientists who worked with this stuff for a hundred years, they all had it wrong. . . It's sort of a bit like pin the tail on the donkey, except you don't know if it's a tail, if it's a donkey, or which end is which anyway.

Desmond Collins, Paleontologist

Des Collins is a Senior Curator at the Royal Ontario Museum and since 1975 he has devoted many field seasons to reconnoitering, excavating and collecting fossils from the Burgess Shale of British Columbia. Every summer, he makes the spectacular drive through the Canadian Rockies to the town of Field, British Columbia, just west of the continental divide, descending along the Kicking Horse River to the narrow pocket of the Yoho Valley. The Burgess Shale quarry is now a part of a Canadian national park, but also designated by the United Nations as a World Heritage Site, a place considered so precious and significant to the history of the earth that it is tended like a forbidden shrine. Unless you are Des Collins, or part of his research team, or the occasional film crew, or one of the handful of other people allowed to make the guided trek from Field to the Burgess Shale during the two months of the year when the snow clears, you can't actually go to the quarry.



Fossil Annelid *Canadia spinosa* (top left), *Albertella longwelli* trilobite (middle) and *Hallucigenia* from Chengjiang (bottom). Photos from fossilmuseum.net.

But if you could, you would hike for three hours from a trailhead that begins in Field to an elevation of 7,546 feet where Fossil Ridge runs northwest–southeast from Wapta Mountain to Mount Field. The last 300 feet or so is the real test when you must scrabble up the steep scree after a long trek, but then you're at Walcott's Quarry. If you can tear yourself away from the presence of the world's most famous fossils, the view is breathtaking. Dead ahead to the west is Mount Burgess, to the right, below, is the shimmering, milky green splash of Emerald Lake, and down to the

Walcott Quarry. Photo: University of California Museum of Paleontology.

left, you can pick out the Trans-Canada Highway running along the edge of the braided course of the Kicking Horse River. The quarry itself is about the size of a boxcar, with the chips and slabs of excavation scattered on the down slope, and there, in August of 1909, strange creatures from the distant past whispered to us about an explosive beginning to a half-billion years of animal diversity.

You can hunt fossils in the field, where you also get to swat flies, eat bad food, hike long distances, and sleep on hard ground. Or you can hunt in the cool, dark storage cases in museums. Walcott and his assistants mined about 80,000 fossils from his quarry in the Rockies, and though they were a sensation and were loaned by the Smithsonian to paleontologists around the world, nobody really took a hard look at them. Finally, in the early 1970s, the truth about Charles Walcott's fossils was discovered, not by the accident of a stumbling horse, but by the patient, and systematic inquiry of a paleontologist named Harry Wittington, whose fascination with ancient invertebrates led him to the cabinets where the Burgess treasures were stored.

Wittington concluded that some of the creatures in the Burgess fossils were indeed arthropods, but the rest were ancient examples of the thirty-five body plans — or phyla — for almost every other animal that ever lived. One of the fossils that appears in the Burgess Shale is a worm-like animal called Aysheaia. Although it is not necessarily a direct ancestor of any worm living today, it sure looks like a modern velvet worm. The Burgess Shale also contains, Wittington said, not only extinct species of ultimately successful types of animals, but entire forms of life that departed the planet forever, even as the Cambrian was exploding. The sudden feast of diversity, it seemed, was even more sumptuous than Walcott ever thought possible.

Fossil *Aysheaia* (top) and reconstruction of *Aysheaia* (bottom).

The confusion about the animals of the Burgess Shale is quite understandable before Wittington, Des Collins and others began to decipher their true meaning. Few of the fossils reveal an entire animal, so scientists must recreate ancient creatures piece by piece. "You just never know what you're going to find. So the excitement is finding something completely different and saying: Gee Whiz! Look at that! I've never seen anything like that," says Collins. "But perhaps even more exciting to me is finding something that I'm looking for. I know I have some pieces of a puzzle, so I know there's an animal out there that has this particular structure, or looks a certain way. I want to find the animal all put together. I remember those moments vividly, when you get something and it's never quite what you expect, but it's sort of the last piece of the puzzle."

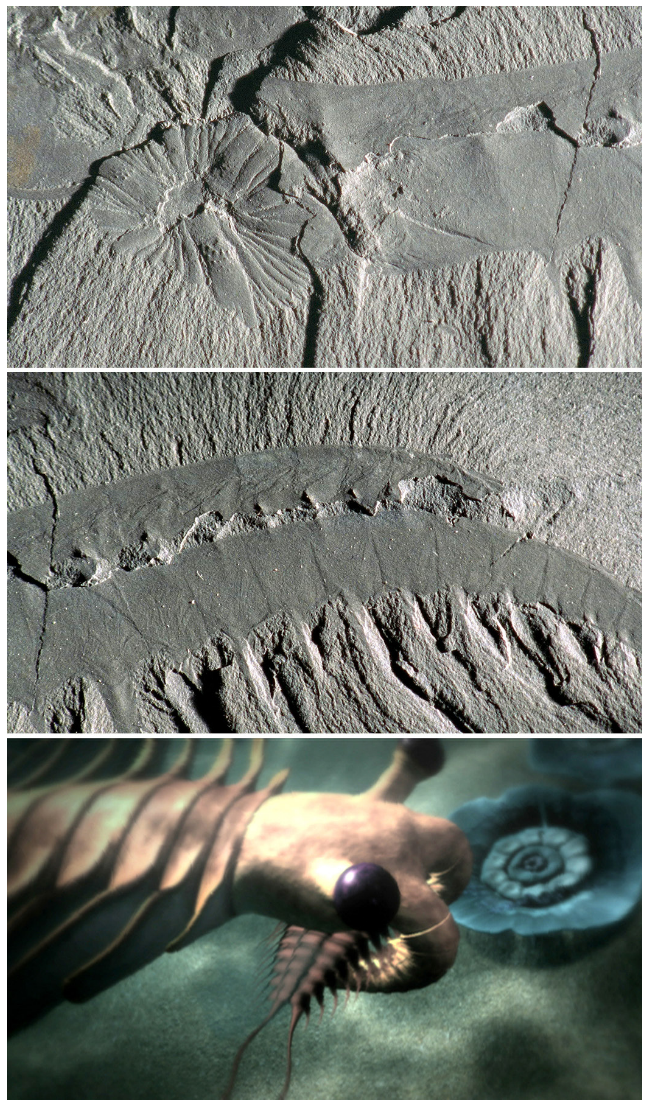
The Puzzle of Anomolacaris

It often takes years and several false starts to piece a single creature together from various fossils. It's a tricky process of trial-and-error, as Collins found with a big Cambrian predator named Anomalocaris (a-NOM-uh-luh-CAR-is). Nothing like this exact animal exists today, though its basic body plan is still used by all arthropods. "Anomalocaris was first described over a hundred years ago in 1887, and at that time, it was based on a claw fossil," Collins recalls. "This was thought to be the body of a shrimp. It seemed to lack a head, but it had what appeared to be legs on it." Another fossil, thought to be a separate animal, looked like the impression of an ancient jellyfish, but these two creatures proved eventually to be part of the same beast, Anomalocaris. "What we thought was the body of a shrimp was actually claws, and what was thought to be a jellyfish was actually the jaws of this much stranger animal," Collins says.

Paleontologist Desmond Collins

"What we've since collected is a complete specimen of Anomalocaris. So we have a pretty good idea. We've got the tail, we've got the head, and here we have a nice model of the whole animal," Collins goes on. "This is the major predator from the main Burgess Shale site. And we even have claws, which are twice this size, so it's conceivable that Anomalocaris got up to three or four feet in length. So, this was a major predator compared to all of the other animals of that particular time. It took over a hundred years to work out what this animal looked like from the first piece that we had."

"And all those scientists who worked with these fossils for a hundred years, they all had it wrong," Collins says. "So, of course, that makes me very nervous that when I'm working with this stuff – particularly if I have something that seems to be a piece of something – since I cannot relate it to something that's alive today, when I try to put it together, the chances are I'm going to be wrong." The self-correcting process of science continues.



Fossil *Anomalocaris* jaws (top) and claws (middle) with reconstruction (bottom).

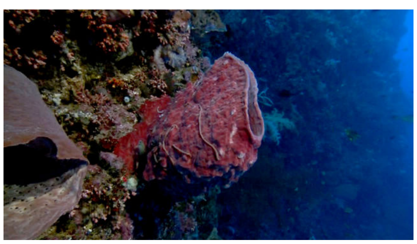
35 Body Plans

One of the amazing things about the animal kingdom right from the Cambrian on is that there are only about 35 body plans, basic designs, yet there are millions of species representing everything from insects to whales. Animals that live in water, animals that burrow under ground, animals that live in coral reefs, animals that swim in the ocean, animals that live on the Antarctic ice.

Rudolf A. Raff
The Shape of Life: Genes, Development, and the Evolution of the Animal Form

And whether or not the pieces of all the fossil animals of the Cambrian explosion fit together, the great message in those fossils remains. The earth is four-and-a-half billion years old, but all the basic body plans of most of the animals that ever lived appeared within a mere twenty million of those years. (The early animal phyla –sponges, cnidarians, and flatworms – almost certainly appeared before the Cambrian.) This is almost too much to be believed, but subsequent study of the Burgess fossils and others from sites on the Cambrian horizon confirm that this period was so rich in diversity that we can call it an explosion of life, a beginning for lineages that still exist over half-a-billion years later.

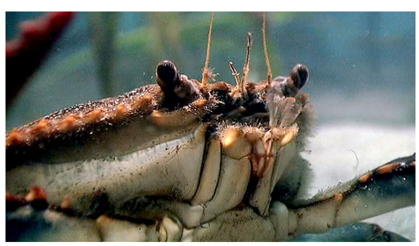
Each of those lineages is called a phylum, from a Greek word meaning 'race.' Because scientific inquiry is constant and self-correcting, debate continues about just how many phyla exist, but 35 is a pretty good number. Most of the 35 are pretty small clubs, and about 99 percent of all the billions of species of animals that ever lived can be grouped into just eight of them. Those eight – sponges, cnidarians, flatworms, annelids, arthropods, molluscs, echinoderms, and chordates – represent virtually the entire animal kingdom.


sponges


cnidarians


flatworms

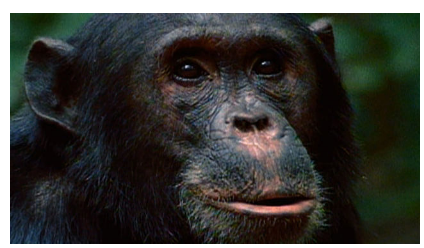

annelids


marine arthropods


terrestrial arthropods


molluscs


echinoderms


chordates

Biology Professor Rudolph Raff

It was as if nature struck upon life's essential designs in a single evolutionary leap. Every new shape of life that has followed the Cambrian has been a variation on those basic architectural themes, and perhaps more remarkably, no new body plans have evolved since. Rudolf Raff, a professor of biology at Indiana University (and the author of a book whose title may sound familiar) is among the legions of men and women who have devoted their lives to sorting through the effects of so marvelous a beginning. Like many biologists, he was drawn into the vortex of science as a child, and his curiosity continues to fuel what is now groundbreaking research on the relationships of animals through time. "What is a body plan? Well," he says, " a body plan is a concept that we made up. And what I mean by this is not that they don't exist, but rather that we recognize that different kinds of animals resemble each other. When we divide them up this way, we realize that there's actually sort of an underlying plan to groups of animals. There are themes of construction."

"Imagine a machine like a Model T Ford," Raff continues. "It's a pretty simple car. The cars of today are the evolutionary descendants of the Model T Ford, more elaborate, but you recognize the body design in there. So it is with the evolutionary animal kingdom. Evolution has produced millions of species of animals. There are probably somewhere between twenty and thirty million kinds of living species right now, and the same was probably true in the past at any slice of time that you take. So in the 500 million or so years since the Cambrian, there has been an immense wealth of animals, everything from dinosaurs to bats to earthworms, and it's all happened within these body plans, thirty-five or so body plans and millions and millions of species."

What Caused the Explosion of Diversity?

How did all the basic themes in animal architecture appear within just twenty million years?

"We really don't know," says Rudy Raff, in that manner of scientists, and children, for whom questions can be much more interesting than answers. But we do have some good clues. "It would seem likely that there's not a single cause for a unique event like that, but there have been a number of hypotheses put forward. Good ones."

First, a question of origins: How could so much anatomical variety evolve so quickly? In particular, must novel evolutionary mechanisms be proposed for such a burst of activity?

Stephen Jay Gould
"Showdown on the Burgess Shale", Natural History Magazine

First, the bloom of diversity might have been a genetic revolution in which the genes that regulate the basic patterning of a body plan had to arise before an animal could make a head, a brain, or features like legs and arms and claws that had to be correctly organized to produce a complex body. Suddenly, in the Cambrian, the genetic code reached sufficient proportions to command and control the production of not just simple animals, such as sponges and jellies, but the more complex races of creatures that still populate the earth.

A second explanation for the Cambrian Explosion may lie in a radical shift in the nature of the planet itself, most likely in the oceans, which were home to all living things at the time. The most obvious of these ecological transformations is a change in the oxygen levels, or a reduction in the levels of other gases that had until that time inhibited growth and diversity. In 2016, scientists are still debating whether there was a change in oxygen levels at the start of the Cambrian.

Perhaps it was the coincidence of ancestral flatworms evolving mobility and the power to hunt their prey that stimulated other forms to defend themselves, which created forces for evolving stronger predatory skills and equipment. Because there is an advantage in eating and avoiding being eaten, the arms race would never end. Perhaps, too, nerves that enable sensing and the coordination of motion, pioneered most primitively by jellies as networks and in the more sophisticated central systems of flatworms, allowed the building of bigger, faster bodies that fed the arms race. Size is a great advantage for a predator. Once a big, fast-swimming, deadly character like *Anomalocaris* was on the scene, the drama of life took on a potential for sudden death that had been absent until that time

As the food web itself became complex enough to provide a multitude of possible ways to make a living, the arms race expanded to one for the control of food. As more and more animals evolved, the battles of the hunter and the hunted intensified. And the explosion of life was the response.