When Life Got Hard

By WILLIAM STOLZENBURG

Animal skeletons emerged abruptly. Why the big hurry?

Marine fossils paint an idyllic scene of animal life in its infancy off the sandy shores of the naked continents some 670 million years ago: Soft coral fronds arch from the ocean floor, jellyfish undulate in the currents, and marine worms plow through the ooze.

But a geologically brief 100 million years later, at the dawn of the Cambrian period, the seascape abruptly changes. Animals suddenly appear cloaked in scales and spines, tubes and shells. Seemingly out of nowhere, and in bewildering abundance and variety, the animal skeleton emerges.

For more than a century, paleontologists have wrinkled their brows trying to explain why – after at least 100 million years of soft, serene multicellular existence – life so hurriedly turned hard. Sophisticated hypotheses abound, some linking the skeletal genesis to changing chemistries of the seas and skies. Yet a recent analysis of these ideas suggests that the oldest – and perhaps most basic – of these explanations deserves the spotlight. From old fossil quarries in Canada and from new ones in Greenland comes fresh evidence supporting the notion that the skeletal revolution was more than a chemical reaction: It was an arms race.

High in the Canadian Rockies of British Columbia, in an extraordinary 540-million-year-old fossil deposit called the Burgess shale, a mid-Cambrian marine community comes to life. Like many less exceptional deposits, the Burgess harbors mild-mannered mollusks, trilobites (the ubiquitous, armored "cockroaches" of the Cambrian seas) and clam-like brachiopods. But other imprints in the smooth black shale dispel any image of a peaceful prehistoric aquarium. In these waters lurked a lethal cast of predators, eyeing little shells with bad intent: *Sidneyia,* a flattened, ram-headed arthropod with a penchant for munching on trilobites, brachiopods and cone-shelled hyolithids; *Ottoia,* a chunky burrowing worm that preferred its hyolithids whole, reaching out and swallowing them with a muscular, toothed proboscis; and even some trilobites with predatory tastes.

Photos courtesy Smithsonian Institution

Thanks to a rapid burial under fine sediment, which sealed out scavengers and agents of decay, the Burgess shale preserves a unique snapshot of life in the heyday of the skeletal revolution. Though Burgess excavations began early in this century, only in the past 20 years have paleontologists begun detailed reconstruction of the shale's hunters and hunted. Their findings have helped resurrect the arms race hypothesis: the 80-year-old idea that skeletons evolved primarily as fortresses against an incoming wave of predators.

Witness *Wiwaxia,* a small, slug-like beast sheathed in a chain-mail-like armor. With two rows of spikes running along its back, *Wiwaxia* was the mid-Cambrian analogue to a marine porcupine. Paleontologist Simon Conway Morris of the University of Cambridge in England, who reconstructed the creature from a mashed mass of fossil scales and spines, says *Wiwaxia* was likely dressed for defense.

Plastic models of Ottoia *(left) and* Sidneyia, *two of the predominant predators known from the Burgess shale. Their fossils show small, shelled animals in the gut.*

Even more telling are the chinks in its armor. Some of *Wiwaxia's* spines appear to have broken and healed, says Conway Morris, who suspects that predators snapped them off. In recent years, he and others have also noticed bite-sized chunks missing from fossil trilobites (SN: 7/29/89, p.78).

The healed wounds of trilobite and *Wiwaxia* specimens suggest that predators strongly influenced the elaborate new skeletal designs of the mid-Cambrian, asserts evolutionary biologist Geerat Vermeij of the University of California, Davis. In the December 1989 PALAIOS, he reexamines several of the major hypotheses explaining the skeletal revolution, and concludes that predation was the primary factor. Nonlethal injury to skeletons, Vermeij writes, "would demonstrate that the organism sustaining the injury was able to survive despite the onslaught, and therefore that some of its attributes (including those of the skeleton) served a protective function."

What sort of creature could gouge such wounds in a husky trilobite? British paleontologists Derek Briggs of Bristol University and Harry Whittington of the University of Cambridge believe they have found a likely culprit embedded in the Burgess shale. In 1985, they unveiled their reconstruction of *Anomalocaris,* the largest of Cambrian predators. Fitting no other major animal design known, this half-meter-long "terror of the trilobites," as Briggs and Whittington have called it, glided through the seas with ray-like fins and chomped with a ring of spiked plates that dispatched trilobite shells like a nutcracker, the two speculate. Its bite probably formed a W shape, nicely matching some of the trilobite wounds they have examined.

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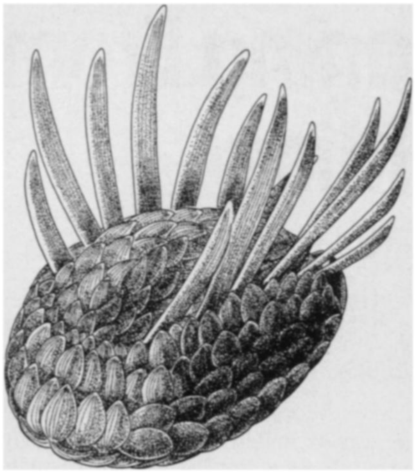
In all fairness, *Anomalocaris* has been caught holding the weapon but never the victim. Other Burgess predators have not fled the scene so quickly, however. For instance, paleontologists have found fossils of the arthropod *Sidneyia* and the carnivorous worm *Ottoia* with shelly animals still in their guts.

Yet even the inside of a stomach might not spell doom for the ingested prey — given a properly equipped skeleton. Vermeij cites the example of some modern-day clams with hermetically sealed shells, swallowed whole by one type of starfish. "They can sit there for 14 days in the digestive system," he says. "Finally the sea star excretes them, and they just go their merry way."

Though it depicts the skeletal drama unfolding a staggering 540 million years ago, the Burgess shale missed the opening act. The curtains went up about 30 million years earlier, when a flourish of fauna with hard little tubes, cones, scales and needles — collectively called the "small shelly fauna" — burst upon the scene. Many of these structures consisted of calcium compounds, leading some paleontologists to look to oceanic chemistry for skeletal explanations. Geochemical models suggest that oceanic calcium levels were increasing as animal skeletons became more diverse and elaborate. Noting that high concentrations of calcium in animal tissue can prove lethal, proponents of the detoxification hypothesis contend that skeletons evolved as calcium receptacles for early soft-bodied creatures needing to dump the excess mineral from their tissues.

Vermeij questions that hypothesis, citing the energy expense of producing such shells. "If an organism really needs to get rid of calcium in a desperate way, it will do it any way it can," he says. On the other hand, shells made under less dire conditions, Vermeij suggests, would tend to be more tidily constructed. "But the problem is, you're seeing inefficient forms in places such as fresh water, where the levels of calcium carbonate are generally low."



Marianne Collins, courtesy Stephen Jay Gould

Paleontologist Kenneth M. Towe at the Smithsonian Institution in Washington, D.C., adds, "If [detoxification] is the reason, how did those organisms without calcium skeletons detoxify themselves? You don't need a skeleton to detoxify calcium. You can just dump it into the ocean."

Levels of atmospheric oxygen also appeared to rise in concert with the skeletal revolution. Some researchers have proposed that the new metabolic energy supplied by oxygen allowed for larger animals, which in turn required more rigid structural supports. "But most of the early shell-bearing animals were extremely small," counters Vermeij. He favors the idea that oxygen merely afforded animals the luxury of fancier skeletal architecture.

"Predation, rather than detoxification or size increase, was largely responsible for the origin and subsequent elaboration of calcareous skeletons," Vermeij asserts.

From the treacherous maw of *Anomalocaris* to the healed wounds of *Wiwaxia,* much of the support for the arms race argument hinges on the Burgess shale collection. But what about the small shelly fauna that emerged 30 million years earlier? For an arms race hypothesis to be complete, predators must have roamed then, too.

Conway Morris/Univ. of Cambridge

Armored relatives: Wiwaxia *(upper left) and its proposed ancestor, a newly discovered halkieriid. The spines of* Wiwaxia *apparently thwarted predators, but the shells at each end of the halkieriid come as a baffling surprise.*

"Unfortunately, if you [look at] a typical shelly fauna, a normal fossil fauna, you won't see any predators at all, because most predators in a paradoxical sense are soft-bodied and are not preserved," says Conway Morris. Hence, most evidence for predators of shelly fauna rests on the injuries the attackers left behind. In 1968, Stefan Bengtson of the University of Uppsala, Sweden, described several early Cambrian specimens of the small, clam-like *Mobergella,* each with a neat round hole through the apex of its shell. To this day, Bengtson remains unsure whether the shells represent an entire skeleton or merely a cap to a tubular burrowing animal. But he has strong convictions about the holes in *Mobergella,* believing they did not get there by daily wear and tear.

"Each hole appears on the central, most conical part of the shell, where it is thinnest," Bengtson explains. "The predator that attacked *[Mobergella]* appeared to have been drilling through the thinnest part of shell to get to the soft interior."

Something might have wanted to bore into the skeletal fortress of the early Cambrian *Mickwitzia* as well, but it would have run up against a second line of defense. Paleontologist Mark McMenamin of Mount Holyoke College in South Hadley, Mass., notes that minute holes, or punctae, pepper the shell of the clam-like *Mickwitzia.* These, he believes, served as conduits for secreted antipredator chemicals. In Mexican fossil beds, McMenamin

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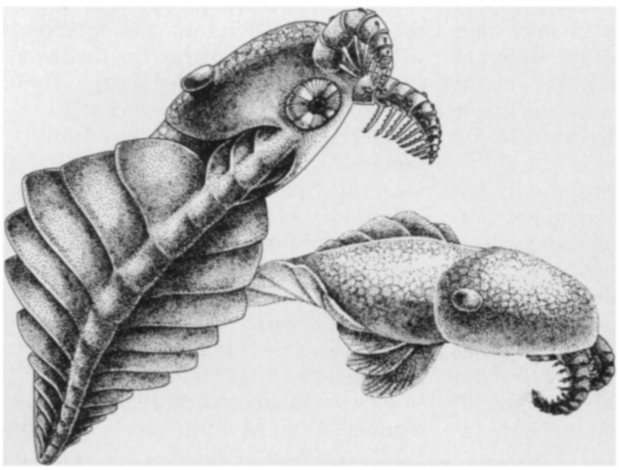

Marianne Collins, courtesy Stephen Jay Gould

Anomalocaris, *the largest creature yet reconstructed from Cambrian fossil beds, is also one of the oddest. Early paleontologists mistook its mouth for a jellyfish, its front appendages for shrimp-like crustaceans. Once assembled, however, it emerged as the king of Cambrian predators.*

benefit MPS VII victims. But until the discovery of the MPS mouse, scientists had no idea which of several chemical forms of the missing enzyme might work, or how much to give. Birkenmeier described some of the latest experiments with these mice at a course in medical and experimental genetics held at the Jackson Laboratory last month.

In one set of experiments, he gave MPS VII mice intravenous doses of human beta-glucuronidase provided by John W. Kyle and William S. Sly at St. Louis (Mo.) University School of Medicine. They had found that by inserting the human beta-glucuronidase gene into bacteria, they could induce the bacteria to make a "raw" version of the human enzyme. But when they inserted the same gene into cultured mouse cells, which are biochemically more sophisticated than bacterial cells, the cells not only manufactured substantial quantities of the enzyme but also processed it in ways that made it more active. It was this form of the enzyme that Birkenmeier injected into his sick mice, and with stunning results.

"The animals are amazingly sensitive to the injections," Birkenmeier says. Even very small doses of the enzyme apparently correct the metabolic defect, reversing some symptoms and, if given early enough, blocking disease progression. He anticipates that ongoing mouse studies will culminate in clinical trials of an intravenous beta-glucuronidase treatment for children.

The benefits of early intravenous beta-glucuronidase supplements might not have seemed so exciting a few years ago, Birkenmeier says. Until recently, physicians had no way to identify MPS VII children before glycosaminoglycans accumulated with irreversible effects. But a new test, developed by Chester B. Whitley and his colleagues at the University of Minnesota in Minneapolis, appears capable of making this early diagnosis. The test, described in the February 1989 CLINICAL CHEMISTRY, assays glycosaminoglycan levels in urine. Those levels are elevated in newborns with mucopolysaccharidoses such as MPS VII, tipping off physicians to the impending problem.

Beyond their usefulness for testing conventional therapies, MPS VII mice show promise as test subjects for gene therapy. Kyle and others at the St. Louis University School of Medicine, working with Birkenmeier and his colleagues from the Jackson Laboratory, recently inserted the gene for human beta-glucuronidase into MPS VII mice. These genetically engineered animals, now able to make their own beta-glucuronidase, show no signs of the storage disease. Details of the work appear in the May PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES (Vol.87, No.10).

Although gene therapy for humans with MPS VII remains years away, the engineered mice hint at a permanent cure for this and related disorders, Birkenmeier says. He notes that MPS VII is "relatively rare" in humans, "but taken together, lysosomal storage diseases represent a significant clinical problem," especially among certain ethnic groups such as Ashkenazi Jews.

For example, two of the more prevalent lysosomal-storage disorders — Gaucher's disease and Tay Sachs disease — strike one in 600 and one in 3,000 Ashkenazi Jews, respectively, according to figures compiled by geneticist Victor McKusick at the Johns Hopkins University School of Medicine in Baltimore. And while physicians worldwide have diagnosed only 25 to 30 people with MPS VII, one in 70,000 individuals in Israel is born with MPS II, while MPS III affects one in 24,000 in the Netherlands.

Birkenmeier proposes that widespread application of the infant screening test for MPS, followed by intravenous therapy for those testing positive, could go a long way toward preventing onset of the disease. And in the long run, he says, genetic manipulation of patients' cells may provide a permanent cure.

Although his work with MPS mice continues, Birkenmeier has broadened his interests to encompass inborn intestinal disorders. By intercepting ill mice on their way to Animal Health, he hopes to do for these pernicious diseases what he's begun to do for lysosomal-storage diseases.

Already, Birkenmeier has initiated tests on a few candidate mice to see if their intestinal problems have a genetic basis. It may be years before the work leads to useful models of human digestive diseases, he concedes. But he also knows that with perseverence and a little bit of luck, some runted rodent may emerge with the answer to many people's most gut-wrenching problems. □

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has found that predators riddled the unperforated shells of other animals but left *Mickwitzia* alone.

Mickwitzia and *Mobergella* notwithstanding, paleontologists have only sketchy evidence that early Cambrian skeletons served as predator-resistant armor. Most of the small shelly fossils from that era remain an odd assortment of caps and cones, spicules and scales. "And they're largely enigmatic in that these wretched things fell into thousands of bits when they died," says Conway Morris, who likens the reconstructor's task to throwing a jigsaw puzzle out of an airplane and reassembling it on the ground. So far, the shards offer few hints of defensive functions.

Yet as excavations proceed at quarries around the world, new finds strengthen the case for an early Cambrian arms race. From an extraordinary fossil bed discovered in 1984 in north Greenland — predating the Burgess shale by perhaps as much as 15 million years — comes a jigsaw puzzle already assembled: a suspiciously familiar, slug-like beast sheathed in chain-mail armor. In the June 28 NATURE, Conway Morris and John S. Peel of the Geological Survey of Greenland in Copenhagen, Denmark, describe an unprecedented discovery: the complete skeleton of an early Cambrian "halkieriid," which they propose as the long-sought ancestor of the armored slug *Wiwaxia*.

Though the halkieriid lacks *Wiwaxia's* dorsal spines, it sacrifices nothing to strangeness. To the bafflement of its discoverers, the creature sports a disproportionately large, saucer-like shell at each end of its elongated body. Bengtson speculates that these served to plug the entrance to the halkieriid's U-shaped burrow. McMenamin, adding yet another twist, says the posterior shell so resembles the clam-like *Mickwitzia* that he now believes *Mickwitzia* was not an organism unto itself, but rather a piece of armor worn by a larger animal that resembled the halkieriid.

From another recent fossil discovery at a quarry in south China — which appears even older than the Greenland site — emerges the bizarre *Microdictyon*. Unveiled last year by Chinese paleontologists, *Microdictyon* is a wormish creature with a row of pointed appendages and a body studded with oval phosphate plates. Bengtson, who says the animal must have looked "like something out of a bad dream," thinks the plates might have served as some sort of antipredator armament.

Bit by bit, the skeletal puzzle comes together. Conway Morris says about 30 quarries worldwide are beginning to yield Burgess-quality fossils, with many more sites yet to be discovered. And he believes it's only a matter of time before paleontologists track down the original cast of predators that might have helped incite the skeletal stampede. Fossils now show, for instance, that the trilobite-chomping *Anomalocaris* identified at Burgess also roamed the early Cambrian seas.

"When we find the equivalent of the Burgess shale right at the base of the Cambrian period, as surely we will, we will find that there are all sorts of interesting predators," Conway Morris predicts. "Ultimately, I think we're going to be able to integrate the whole thing into quite a nice story." □