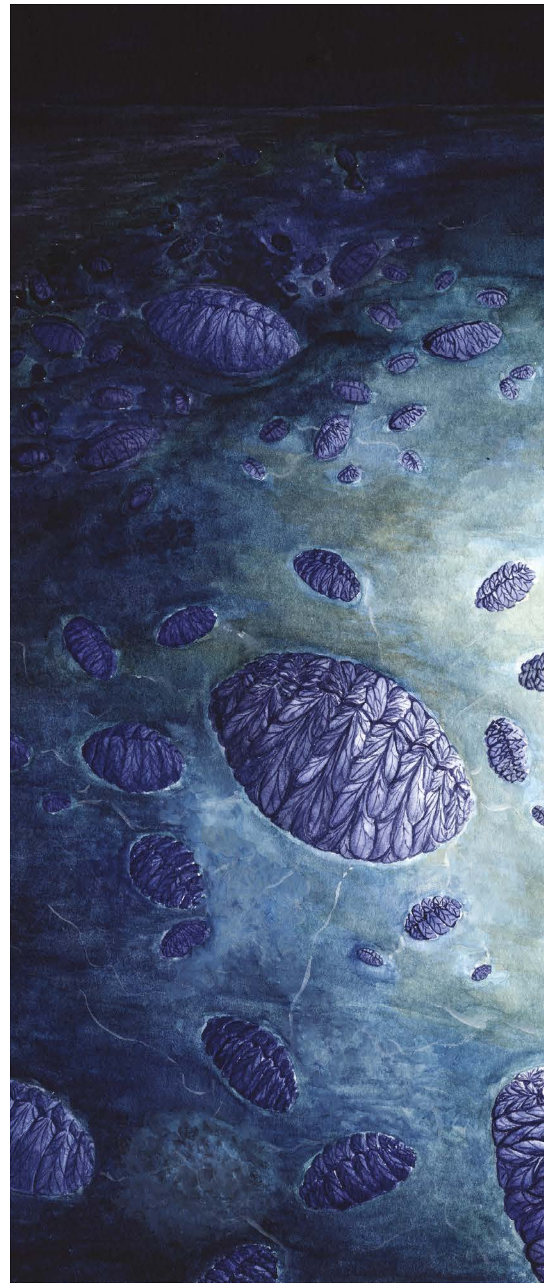
Feature

THE BIZARRE SPECIES THAT ARE REWRITING ANIMAL EVOLUTION

Early fossils with guts, segmented bodies and other sophisticated features reveal a revolution in animal life — before the Cambrian explosion. **By Traci Watson**



The revolutionary animal lived and died in the muck. In its final hours, it inched across the sea floor, leaving a track like a tyre print, and finally went still. Then geology set to work. Over the next half a billion years, sediment turned to stone, preserving the deathbed scene. The fossilized creature looks like a piece of frayed rope measuring just a few centimetres wide. But it was a trailblazer among living things.

This was the earliest-known animal to show unequivocal evidence of two momentous innovations packaged together: the ability to roam the ocean floor, and a body built from segments. It was also among the oldest known to have clear front and back ends, and a left side that mirrored its right. Those same features are found today in animals from flies to flying foxes, from lobsters to lions.

Palaeontologist Shuhai Xiao marvels at the tracks left by this creature, *Yilingia spiciformis*, and how they captured evidence of its movement. In his cluttered office at Virginia Tech in Blacksburg, he shows off a slab of beige resin — a reproduction of the fossil, which was found in China's Yangtze Gorges region and is now kept in a Chinese research institute. The replica captures a snapshot of a moment from 550 million years ago. Xiao, whose team formally described *Yilingia* last year[1], traces the bumpy tracks it made immediately before its death. "It was just moving around, and it died suddenly," he says.

But that's not the end of this creature's story. Although nobody knows which category of life it belonged to — the group that includes earthworms is one possibility — *Yilingia* is helping to fill in key details about the evolution of animals. Most importantly, *Yilingia* shows that some quintessential animal traits had appeared half a billion years ago, earlier than previous definitive evidence, Xiao says.

Yilingia is not the only creature from that region to provide some of the earliest fossil evidence for an important animal feature. In 2018, Xiao and his team reported[2] on tracks found in the Yangtze Gorges consisting of two parallel rows of dimples. The researchers propose that the trails were made by an animal from 550 million years ago that might have been able to burrow and had multiple pairs of appendages — which would make it one of the earliest-known animals with legs.

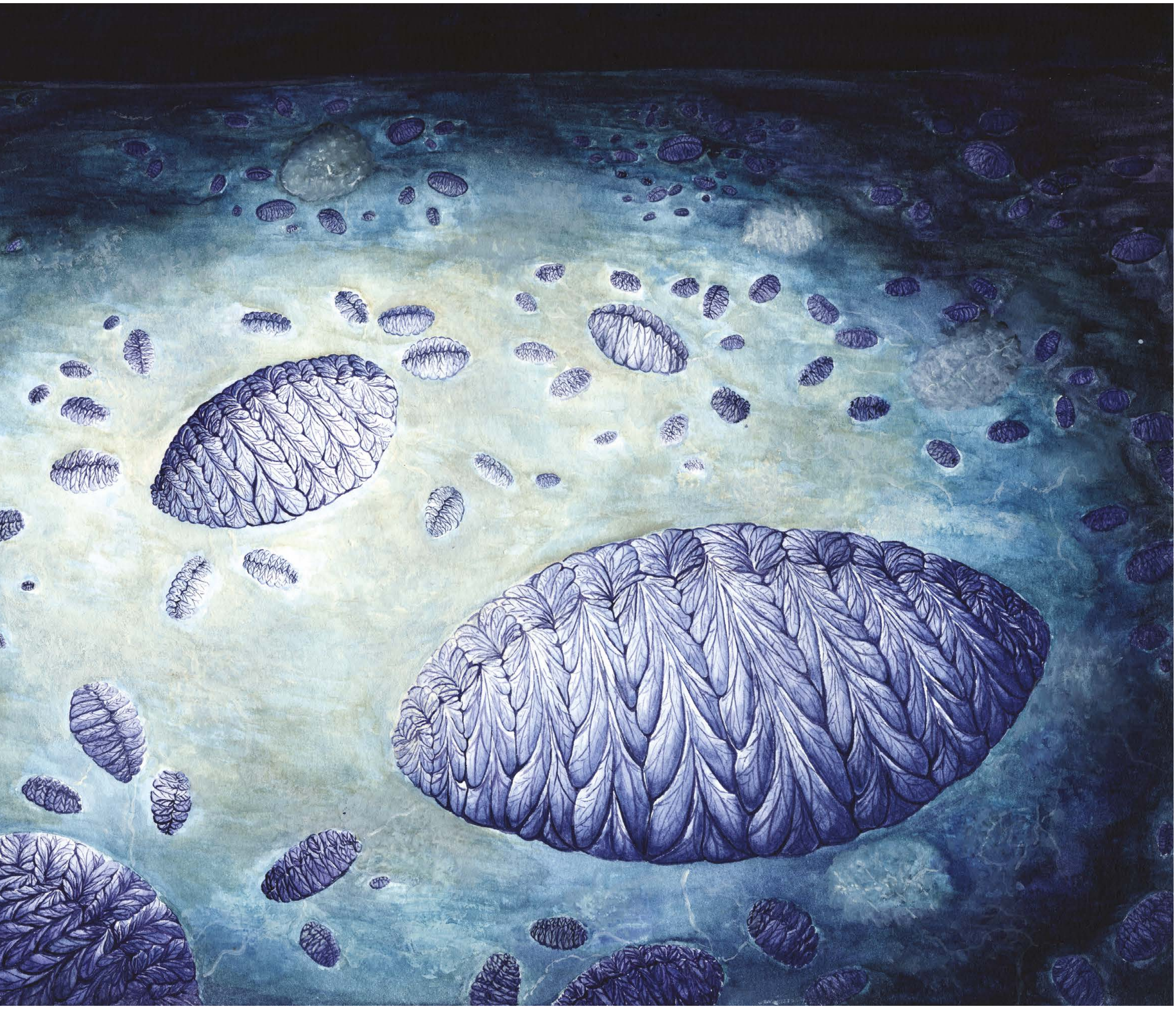
These Chinese fossils hail from a time right before the Cambrian explosion, the evolutionary transformation when most of the animal groups that populate the planet today first made their appearance in the fossil record. Scientists long regarded the boundary between the Cambrian period and the Precambrian as a dividing point in evolution — a transition from a world in which simple, strange organisms flourished, to a time when the seas teemed with complex creatures that are the forebears of nearly everything that followed.

But a growing number of findings reveal that the time slice just before the Cambrian, known as the Ediacaran (635 million to 541 million years ago), was a pivot point of animal evolution — a period that includes the earliest fossil records of anatomical innovations, such as guts and legs, and the first appearance of complex behaviours such as burrowing. The insights into the Ediacarans' powers lend support to a provocative idea: that the Cambrian explosion, that iconic evolutionary burst, was actually less revolutionary than many had thought.

The Cambrian explosion "is just another phase of evolution", says palaeobiologist Rachel Wood at the University of Edinburgh, UK. "It's not a single flash event. It could not have happened without previous waves of innovation."

Tumultuous times

The Ediacarans' innovations came against a backdrop of planetary cataclysms. During this time, Earth was still recovering from a long, shivery chapter when ice covered much of the seas. A gigantic meteor slammed into what is



Organisms named *Fractofusus* cover the sea floor some 560 million years ago, in a reconstruction of fossils from Newfoundland, Canada.

now Australia and probably kicked up enough dust to trigger catastrophic changes around the globe. The planet's very surface was splitting: during the Ediacaran, one supercontinent broke apart and another took shape as land masses smashed together. On the continents, no plants grew. In the ocean, oxygen levels swung wildly.

Scientists once thought that complex life did not start until after all this tumult. In Charles Darwin's day, no fossils had been found below the rock layers documenting the Cambrian explosion. That blank rock record troubled Darwin, who reasoned that if his theory of evolution were correct, there must have been life before the Cambrian's riches. "The case at present must remain inexplicable," he wrote in *On the Origin of Species* in 1859.

'Darwin's dilemma' would remain unsolved for a century. In the 1930s and 1940s, researchers found intriguing imprints in rocks in Australia and elsewhere, but those rocks were not definitively Precambrian. Then, several English schoolchildren finally gave the Ediacarans their big break in 1957. Scrambling through a local quarry, the students noticed a leaf-shaped imprint in the ancient stone. Geologist Trevor Ford at the University of Leicester, UK, went to see it — and recognized that it had been made by a living thing. Ford's paper[3] about the imprint provided definitive evidence that large, complex species lived in the Precambrian. He ventured that the type of organism was probably "an algal frond".

It almost certainly wasn't. Ford's proposal was among the first in a long list of mistaken ideas about the identity of Ediacaran organisms. As more were discovered, scientists tried valiantly to place them on the tree of life. Some of the fossils were towering structures that stood one metre tall; others resembled deflated air mattresses. They have been called lichens and algae, fungi and bacterial colonies. "Basically any interpretation you can name has been suggested," says geobiologist Lidya Tarhan at Yale University in New Haven, Connecticut.

Finally, an audacious theory broke through the welter of competing claims. In the 1980s and 1990s, palaeontologist Adolf Seilacher at the University of Tübingen in Germany proposed[4,5] that many Ediacaran life forms were not animals, but instead belonged to a single, bizarre group that he called the Vendobionta. These organisms were "an evolutionary experiment that failed" when formidable predators arrived on the scene, Seilacher wrote. His ideas have fallen out of favour, but they challenged researchers to question their assumptions. "At the time it was brilliant thinking," says geobiologist Simon Darroch at Vanderbilt University in Nashville, Tennessee. "Before that, everyone assumed they were all jellyfish, which was even more wrong."

Now, most scientists are reaching agreement that the Ediacarans were a grab bag of disparate life forms, rather than the self-contained group proposed by Seilacher. "It's inappropriate to consider them a failed experiment," says palaeontologist Frances Dunn at the University of Oxford, UK. "They represent the ancestors, probably, of lots of different things." Many scientists – although not all – are also signing up to the idea that some fraction of the Ediacaran organisms were probably animals, including some that don't look like any animal alive today.

That idea dovetails with genetic evidence that animals, or metazoans, first appeared more than 600 million years ago, well before the Ediacaran. There are no definitive fossils to illustrate the dawn of the animals, but the early metazoans were probably small, soft, simple things, including ancestors of modern creatures such as sponges and corals. Eventually, animals developed left–right symmetry, which is packaged with a gut, mouth and anus.

But it's not easy to define which fossils are animals and which are not. "Would we know the first metazoan if we tripped over it?" Wood wonders. "Is our search image correct?" Those questions still dog scientists.

Insight from imprints

Although the Ediacaran fossils have bedevilled researchers for decades, new techniques are coaxing fresh insights out of previously intractable imprints. Take the baffling organisms in the genus *Dickinsonia*. Rounded and flat, they resembled segmented bath mats only a few millimetres thick, although they could reach nearly 1.5 metres in length. Their strange construction spawned theories that they were protists – a diverse group of mostly single-celled organisms that includes protozoa and some algae – or lichens, although many researchers suspected that they were animals.

To try to settle the long-standing dispute, geobiologist Ilya Bobrovskiy, now at the California Institute of Technology in Pasadena, and his colleagues took a biochemical approach. Bobrovskiy used tweezers to harvest thin films of organic matter – the remnants of *Dickinsonia* specimens that lived more than 550 million years ago. Analysis of the fat molecules in these biofilms showed that they were breakdown products of cholesterol, which is found in animals' cell membranes[6]. "*Dickinsonia* was indeed an animal," Bobrovskiy says.

> "BASICALLY ANY INTERPRETATION YOU CAN NAME HAS BEEN SUGGESTED."

Dickinsonia was a rather simple animal: it showed no evidence of a mouth or a gut. But earlier this year, scientists detailed what might be the oldest-known animal that had both. Called *Ikaria wariootia*, it lived at roughly the same time as the *Dickinsonia* specimens that Bobrovskiy's team studied, or perhaps earlier[7].

This discovery resolves a long-standing Ediacaran whodunnit: what made the narrow, twisting burrows that cut through Ediacaran sediments? They are among the most common Ediacaran calling cards, but are so small – only 1.5–2 millimetres wide – that they must have been created by an elusively tiny organism. "We never thought we'd see it," says palaeontologist Mary Droser at the University of California, Riverside. Then she got her hands on a 3D laser scanner.

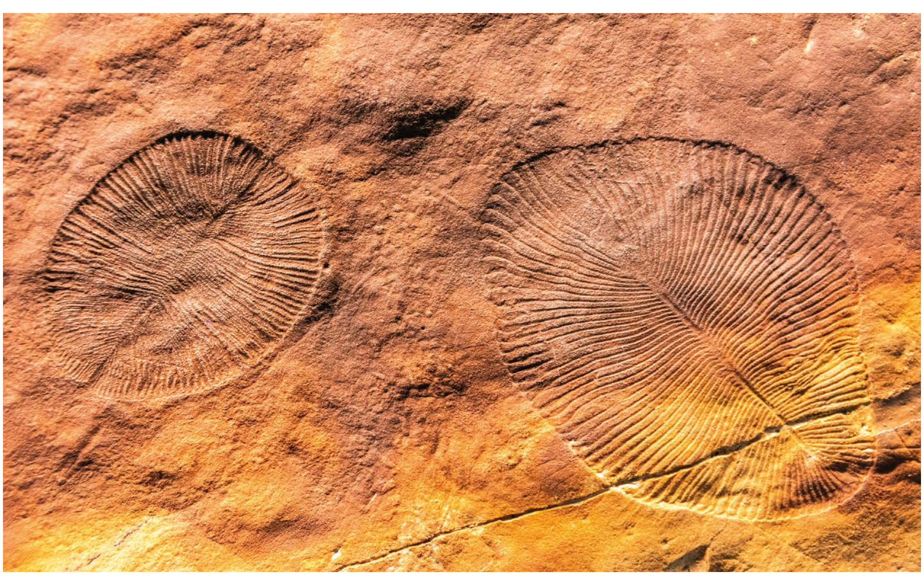
Droser and her colleagues used the scanner to image hundreds of tiny blobs found near the twisting burrows. The team's high-resolution 3D reconstructions show that the blobs were, in fact, organisms[7]. They were smaller than grains of rice, but they had left–right symmetry and both a front and back end, and features of the burrows suggest that the creatures could control where they moved. Previous analysis showed that some burrows wend into and out of the buried bodies of larger organisms, implying that *Ikaria* was a scavenger – the earliest known. Droser's team suggests that, to support *Ikaria*'s burrowing and scavenging habits, the tiny animal probably had a mouth, anus and gut.

More evidence that Ediacarans had guts comes from tubular organisms called cloudinids that arose around 550 million years ago. Using high-resolution X-ray imaging to peer inside cloudinids' outer tubes, researchers saw a long, cylindrical feature, which the authors say is the oldest gut in the fossil record[8]. The team found this feature in a cloudinid that most probably belonged to the genus *Saarina*, and it bolsters the case that some cloudinids were animals with left–right symmetry[8], says palaeobiologist and study co-author Jim Schiffbauer at the University of Missouri, Columbia. The gut's shape and other clues hint that *Saarina* could be an early annelid, an animal grouping that includes modern earthworms.

Alien animals

New approaches are producing evidence that even the most alien-looking Ediacarans might have been animals. Take the 'frondose' Ediacarans, which were built from collections of miniature branches reminiscent of a fern's lacy foliage. Some frondose organisms resembled heads of lettuce, whereas the organism *Charnia masoni* looked like a palm branch stuck into the sea floor. *Charnia* and its close relatives had a 'pseudo-fractal' organization like that of no living creature: the fronds were made up of branches, which were made up of sub-branches, which were made up of still-smaller branches.

Dunn and her colleagues borrowed tools from developmental biology to understand these oddities. The researchers noted that



ZEYTUN TRAVEL IMAGES/ALAMY

Evidence indicates that *Dickinsonia*, an iconic organism of the Ediacaran period, was an animal.

ZHE CHEN/NANJING INST. GEOL. PALAEONTOL.; SHUHAI XIAO/VIRGINIA TECH

A fossil from South China shows the worm-like creature *Yilingia spiciformis* (right) at the end of a track that it made in the sea floor.

Charnia's fronds invariably have the same outline: widest at the bottom, smallest at the tip, with no short branches in the middle. This uniformity, a product of how the organism grows, is not seen in plants or algae[9]. Despite the other-worldly appearance of *Charnia* and its kin, "they're more closely related to animals than they are to anything else", Dunn says.

Researchers studying the Ediacaran have revealed other frondose quirks by turning to the tools of modern ecology. One such technique is spatial analysis, which involves ultra-precise mapping of a large set of organisms that are preserved precisely where they lived – information that is rarely available in palaeontology. But scientists have exactly such an array at their disposal in Newfoundland, Canada, which has thousands of frondose imprints. Among them are examples that date back 571 million years, making them the oldest-known organisms that are big enough to be seen without magnification.

Some of Newfoundland's most abundant residents from around this time belong to the genus *Fractofusus*, whose members looked like mounds of fronds in the shape of an overturned saucer. Like its cousin *Charnia*, *Fractofusus* might have been an animal with no modern analogue. Spatial analysis showed that many large *Fractofusus* specimens are surrounded by clusters of small ones[10]. "Children," says palaeobiologist Charlotte Kenchington at the University of Cambridge, UK, who was a member of the team that published the findings[10] in 2015. This pattern suggests that *Fractofusus* multiplied in part by shooting out long runners on which its young developed.

In a paper[11] published earlier this year, scientists describe long, thin, fossilized threads, some stretching 4 metres, between frondose organisms in Newfoundland. These threads might have been reproductive runners, and could also have been used for nutrient transport or communication. Perhaps these organisms were "acting in each other's best interests rather than just for themselves", says palaeobiologist Alex Liu at the University of Cambridge, who co-wrote the paper[11].

Before the Big Bang

As evidence mounts for Ediacaran innovation, a group of researchers is using these finds to question an icon of evolutionary history: the Cambrian explosion. In the past, researchers often spoke of this event as the Big Bang of evolution – a single, supreme episode that had no prelude and suddenly changed everything. But some researchers take the view that Ediacaran organisms were the founders of this revolution. The burst of new species in the Cambrian "didn't just come out of thin air", says Wood. "It must have been derived from something in the Ediacaran."

A common view holds that many Ediacaran organisms vanished at the Ediacaran–Cambrian boundary some 540 million years ago. But while excavating in a remote spot in Siberia, Wood and her team found Cambrian-type fossils, such as animals that lived in mineral-laden, tube-shaped shells, in Ediacaran-age rock[12].

Wood and her co-authors cited these fossils in a provocative 2019 paper[13], which also noted that Ediacaran animals capable of burrowing into sediments survived into the Cambrian period. The ability to burrow is a hallmark of that time, when animals dug so enthusiastically that they tore up the sea floor, creating new ecological niches. But the Ediacarans took the first step, the authors say. The vaunted Cambrian explosion, "was simply one phase" in the rise of animal diversity, they contend.

All of these findings tell a new story of animal evolution – but it is not yet clear whether the revision will stick. Some palaeontologists say that Wood's argument, in trying to give the Ediacaran its due, gives short shrift to the Cambrian explosion – which marked the appearance of a vast number of creatures that fit clearly into modern animal groups. Xiao agrees that some Ediacaran animals survived into the Cambrian, but he argues that the big picture shows a mass die-off at the boundary between the two periods. And invertebrate palaeontologist Jean-Bernard Caron at the Royal Ontario Museum in Toronto, Canada, questions Wood's tally of Ediacaran species that survived into the Cambrian. "We don't really have the fossil record to support that," he says. Wood responds that although the critique is fair, it's clear that multiple Cambrian-style creatures first appeared in the Ediacaran.

For all the contention, however, some researchers think that answers are just around the corner. Continued work on biomarkers could pin down whether various Ediacaran organisms were, in fact, animals. And palaeontologists are excavating new Ediacaran finds in places such as Iran and Russia, Darroch says. The latest approaches, such as spatial analysis, hold promise too, says Xiao. These could flesh out – at long last – what was going on in the oceans during the pivotal Ediacaran period.

"I would just love to be swimming over these communities and see, finally, how are they really growing? What on Earth are they?" Wood says. "So much would become obvious."

Traci Watson is Senior Editor for News and Research Highlights at *Nature* in Washington DC.

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