News & views

Palaeontology

Fossils reveal the deep roots of jawed vertebrates

Matt Friedman

Scarce evidence indicates that key evolutionary steps for jawed vertebrates occurred during or before the Silurian period, 444 million to 419 million years ago. Fossil finds pull back the curtain on this interval. **See p.954, p.959, p.964 & p.969**

Nearly 200 years ago, geologist Roderick Murchison designated a set of rocks along the border of Wales and England as the Silurian System[1]. Among them, he found fragments of fossil fish jaws, spines and scales that he noted were "the most ancient beings of their class" and "wholly unlike" the remains found in overlying rock strata. Murchison's Silurian scraps contrasted with the abundant, well-preserved fossils of jawed fishes known from younger deposits. Nearly two centuries of palaeontological efforts worldwide have reinforced this pattern. The diversity of jawed-fish remains from the Devonian period (419 million to 358 million years ago) – the Age of Fishes – suggests an evolutionary history that extends deep into or even before the sparsely fossiliferous Silurian period (444 million to 419 million years ago)[2].

Four papers in *Nature*, by Gai *et al.*[3], Andreev *et al.*[4,5] and Zhu *et al.*[6], introduce a piscine menagerie from early Silurian deposits in China (Fig. 1). Dating to between 439 million and 436 million years ago, these remarkable finds bring a once murky interval into sharper focus. They establish unequivocally an ancient origin for jawed vertebrates and clarify how some of their signature features might have evolved.

In the days since Murchison, fossil finds from the Silurian and older layers of rock have been unevenly spread across the vertebrate family tree. Armoured jawless fishes known as ostracoderms now have a healthy Silurian record; the oldest complete examples of these animals date to even older deposits of the Middle Ordovician epoch, some 465 million years ago. Most, if not all, ostracoderms are more closely related to jawed vertebrates (also called gnathostomes) than they are to living jawless fishes: boneless hagfishes and lampreys. Ostracoderms are therefore instrumental in deciphering how the anatomy of jawed vertebrates arose. Paired fins – evolutionary predecessors of our arms and legs – represent perhaps the most conspicuous gnathostome feature apart from their eponymous jaws.

Gai *et al.* (page 959) contribute to the enduring debate on the origin of paired appendages with their discovery of a 436-million-year-old jawless fish called *Tujiaaspis vividus*, which belongs to an ostracoderm lineage closely related to jawed fishes called galeaspids. The anatomy of galeaspids is unevenly understood. Previous work describes galeaspid heads in meticulous detail[7], but their bodies have remained a mystery until now.

Tujiaaspis lacks regionalized sets of front (pectoral) and back (pelvic) fins of the sort present in jawed fishes, and instead bears a pair of ridge-like flaps extending from the back of the skull towards the tail. Gai and colleagues argue that these continuous fin folds correspond to those of some other jawless fishes

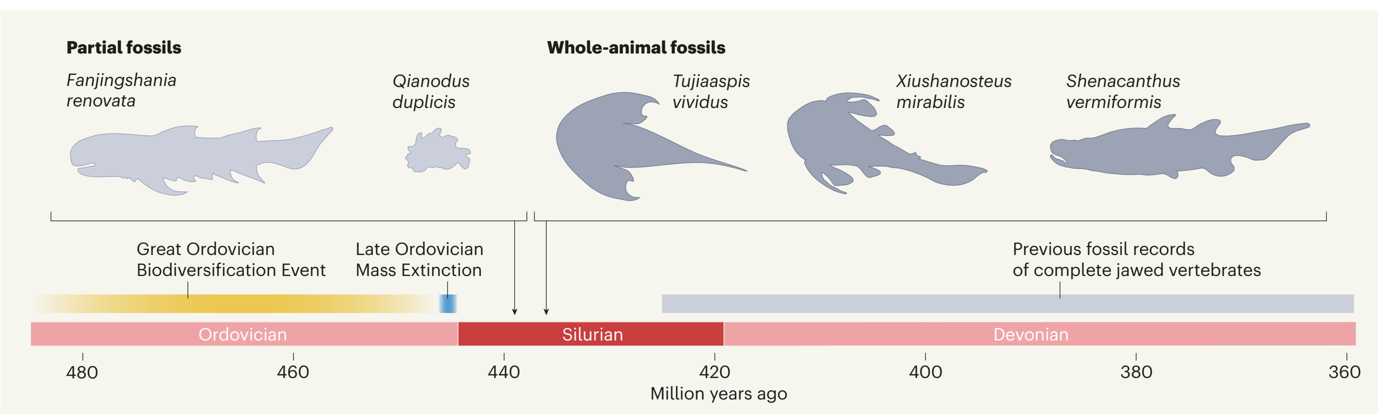

Figure 1 | An early aquarium of fossil finds. A series of fossil-fish discoveries sheds light on the origin of major anatomical features of jawed vertebrates, and suggests that major lineages of these creatures diverged in the early Silurian period or before. These evolutionary splits probably occurred as part of the Great Ordovician Biodiversification Event that preceded the Late Ordovician Mass Extinction. Andreev *et al.*[5] present *Fanjingshania renovata*, which is represented only by isolated 439-million-year-old fragments. A member of the chondrichthyan lineage that contains today's sharks, rays and ratfishes, it provides a robust minimum age for the diversification of living jawed vertebrates. *Qianodus duplicis,* reported by Andreev *et al.*[4], at 439 million years old offers the most-ancient known example of vertebrate teeth and thus of vertebrate jaws. Gai *et al.*[3] present the 436-million-year-old jawless fish *Tujiaaspis vividus*, which provides information about the body and fins of a group called galeaspids. This evidence is relevant to our understanding of the evolution of paired fins and, by extension, human limbs. Zhu *et al.*[6] describe the oldest-known jawed fishes (about 436 million years old) found as complete individuals. These include an armoured placoderm (an extinct set of jawed fishes that branched before the last common ancestor of all living jawed vertebrates) named *Xiushanosteus mirabilis,* and an early chondrichthyan relative called *Shenacanthus vermiformis*.

and represent the evolutionary foundation for the two familiar sets of paired fins. This provides a new twist to a long-standing hypothesis[8], pointing to a stepwise regionalization of the fin fold leading first to pectoral fins (in the lineage leading to gnathostomes and their closest jawless relatives, another ostracoderm group called osteostracans) and then pelvic fins (in jawed fishes themselves).

Although no single fossil is likely to settle the debate between competing models of paired-fin evolution[9], *Tujiaaspis* nevertheless adds an important palaeontological constraint to the problem. What function might the folds have served? Computational fluid dynamics indicates a role in passively generating lift in the absence of regionalized paired fins, providing an adaptation-based hypothesis for the first steps in the origin of a major structural novelty.

In contrast to whole ostracoderm fossils from the Silurian and Ordovician periods, traces of gnathostomes of a similar vintage remain elusive. The skeletal debris that dominates the pre-Devonian record of jawed vertebrates provides few characters to help with identification, leading to a need for ample caution when interpreting such specimens. Fossils of intact animals are more compelling, but vanishingly rare; before 2009, all published examples of more-or-less complete Silurian jawed fishes could be counted on the fingers of one hand[2]. This changed with a dedicated programme of fieldwork in China that led to a flood of discoveries[10–13] dating to the late Silurian, around 425 million years ago.

A fitting encore to those remarkable finds is the trio of papers by Andreev *et al.*[4,5] and Zhu *et al.*[6] on jawed fishes from early Silurian strata that are some 11 million to 14 million years older than the previous discoveries. Unlike material of similar[2] or older[14] ages reported before, these fossils leave little doubt as to their affinities.

The isolated tooth whorls of *Qianodus duplicis* reported by Andreev *et al.*[4] (page 964) are the calling card of jaws, that most essential of gnathostome traits. Andreev and colleagues' second report (page 969) describes *Fanjingshania renovata*, found in the same rock deposits that yielded *Qianodus,* on the basis of partial remains corresponding to a specific subgroup of acanthodians, a collection of extinct fishes related to today's chondrichthyans (sharks, rays and ratfishes). The non-overlapping remains of *Qianodus* (teeth) and *Fanjingshania* (spines, scales and plates) raise questions about whether they belong to different animals, but this does not undermine confidence in their chondrichthyan affinities. This is notable because all living gnathostomes belong to one of two evolutionary lineages: chondrichthyans on one hand, and our own group, the osteichthyans, on the other. Firmly anchored to the chondrichthyan branch, *Qianodus* and *Fanjingshania* indicate unambiguously that the last common ancestor of today's jawed vertebrates lived no later than the earliest Silurian.

Zhu *et al.* (page 954) report an exceptional site, found in a rock deposit only a few million years younger, that yields complete jawed fish fossils — by far the oldest remains preserved in this manner. *Xiushanosteus mirabilis* dominates this palaeontological bonanza. It is unmistakably a type of early armoured jawed fish called a placoderm that, surprisingly, looks broadly similar to species known from rocks many millions of years younger. It is joined by a single specimen of *Shenacanthus vermiformis*, an early relative of chondrichthyans that bears armoured plates on its trunk resembling those of placoderms. There will be a lively debate about the specific features of these newly discovered fossils and the finer details of their classification. But there is no escaping their collective message: the diversification of jawed vertebrates was already well under way by the earliest parts of the Silurian, an exceptional confirmation of earlier inferences from less-complete material[14].

The resulting evolutionary chronology places the early history of jawed fishes amid two formative episodes in the early Palaeozoic era (539 million to 444 million years ago). These vertebrates are likely to be products of what is called the Great Ordovician Biodiversification Event (around 485 million to 445 million years ago) — a sequel to an episode of diversification called the Cambrian explosion (roughly 539 million to 520 million years ago) — as well as survivors of the Late Ordovician Mass Extinction (about 444 million years ago). These finds will force a reconsideration of aquatic ecosystems around this time, as well as prompting another look at old hypotheses concerning major changes to the vertebrate fauna apparent in younger parts of the fossil record[15].

The variety of newly discovered jawed fishes from the early Silurian poses a puzzle. How could a group that was already so diversified leave such a meagre record, particularly of whole fishes? One possibility is that, like their closest ostracoderm relatives[16], the earliest gnathostomes were both geographically and environmentally restricted. But this gap in our knowledge might already be closing. These early Silurian sites have yielded more jawed fishes that are as yet undescribed, placing us on the cusp of an exciting new period, both conceptually and chronologically, for the study of the evolution of early gnathostomes.

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Quantum information

Hybrid technique lights the way for neutral atoms

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An experimental platform that uses two different tools for controlling neutral atoms with laser light combines speed with scalability. The approach provides a crucial step towards realizing innovative quantum algorithms and simulations.

Over the past four decades, researchers have explored a range of fascinating quantum phenomena by inventing creative ways to manipulate large ensembles of neutral atoms with light (see, for example, go.nature.com/3bjqvfr). Hundreds of thousands of atoms can be trapped by laser beams in arrays known as optical lattices[1] and used to simulate the quantum behaviour of materials. Atoms can also be manipulated one by one, using a tool known as optical tweezers — a promising avenue to scalable quantum computing. Now, writing in *Science*, Young *et al.*[2] have developed a platform that combines