The northeastern Pacific Ocean provides the perfect example of this feedback mechanism, because it lies adjacent to the seismically active belt known as the 'ring of fire' and contains large amounts of ice. Du *et al.* hypothesized that the iron-rich ash resulting from the increased volcanism acted as a fertilizer — supercharging the production of organic matter in the surface waters, which, in turn, exhausted all the oxygen in the underlying intermediate waters when it was remineralized.

Conceptually, the authors' idea is straightforward. But, as is often the case in geosciences, even simple ideas are difficult to prove, because high-resolution chronologies are hard to obtain. In this respect, Du and colleagues' study is an exception: through a combination of dating approaches, the authors constructed a precise timescale, spanning the past 20,000 years, for sediment samples that they acquired from two sites in the Gulf of Alaska. These data show that the melting of the Cordilleran Ice Sheet coincided with volcanic phases that occurred at the same time as periods of complete oxygen loss in the northeastern Pacific intermediate waters. Although correlation does not equal causation, the authors' idea provides an elegant explanation for the data.

The link between ice-sheet retreat, volcanism and regional ocean deoxygenation is compelling; however, its global relevance remains unclear. Future research will need to look for similar correlations in other places and at different times. Crucially, however, Du and colleagues' work implies that short periods of iron fertilization can lead to long-lasting oxygen deficiencies in marine ecosystems. This is a key observation in the emerging discussion of how global warming will reduce the oxygen content of the ocean, and suggests that, once waters are entirely devoid of dissolved oxygen, the resulting marine dead zones could affect fisheries for millennia. As a corollary, the authors' findings highlight the potential side effects of large-scale geoengineering ideas, such as the use of iron fertilization to increase the amount of organic matter that sinks from the surface and thus boost carbon sequestration to reduce atmospheric CO_2 concentrations[4].

Our planet is currently experiencing unprecedented challenges as a result of global warming. During the past 50 years alone, the total area of oxygen minimum zones has increased fourfold (see go.nature.com/3fqmazr), and ocean models predict that this trend will continue. Although there is some uncertainty as to how much warming we will see in the near future, geological data suggest that oxygen-free waters might become widespread in a warming world[5]. The loss of oxygen from the ocean affects the world's most-extensive and least-explored ecosystems, with unknown consequences for food security[6]. Du and colleagues' work therefore points to the urgent need for improved understanding of how biogeochemical feedbacks affect the health of oceans across the globe.

Weiqi Yao is in the Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, Guangdong 518055 China.
Ulrich G. Wortmann is in the Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1, Canada.
e-mail: yaowq@sustech.edu.cn

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Palaeontology

An exceptional fossil lizard from the Jurassic period

Arnau Bolet

Lizards and snakes belong to the highly successful group of reptiles called squamates, but a poor fossil record has obscured their early evolutionary history. A discovery now sheds light on this enigmatic portion of the tree of life. **See p.99**

Our collective imagination tends to picture a palaeontologist as an intrepid character similar to the fictional explorer Indiana Jones, searching for ancient material in remote places. But what comes after specimen gathering is frequently ignored. Tałanda *et al.*[1] show on page 99 that finding a fossil is just the start of the journey. Their discovery, a block of rock exposing a few delicate bones on its surface, was hiding a surprise that only modern imaging techniques could reveal. The sample contained an almost complete skeleton of a tiny lizard, with most of its bones in contact in their original anatomical position (partially articulated). The findings could help to answer questions about the first steps in the evolution of squamates, a group of reptiles that includes lizards and snakes.

The history of Tałanda and colleagues' finding starts with the description in 1998 of the first identified specimens of this lizard, called *Bellairsia,* at a site in Kirtlington, UK, and dated to around 167 million years ago[2]. These specimens belong to one of the oldest known fossil assemblages of lizards, but the fragmentary and disarticulated bones prevented recognition of *Bellairsia* as having a form similar to that of ancestral early squamates. Years later, newly uncovered lizard fossils of a similar geological age, including the block studied by Tałanda and colleagues, were found on the Isle of Skye, UK.

After their discovery, some specimens must undergo lengthy mechanical preparation in the laboratory to be properly exposed for study. Occasionally, however, the bones are too small or too delicate to be prepared mechanically, and an imaging method called computed tomography (CT) is instead used to generate 3D digital models that can be studied without harming the fossils. Although CT has long been used in palaeontology, scanning small specimens requires special instrumentation to achieve high-resolution imaging. Tałanda *et al.* used a combination of high-resolution X-ray micro-CT and phase-contrast synchrotron X-ray micro-CT to generate 3D models of all of the elements contained in the block, including those hidden beneath the surface.

By a great stroke of luck, the unveiled complete skeleton was a mind-blowing finding when compared with squamate fossils of a similar age. But the authors were not done yet with their discoveries. This fossil, identified as the most complete and only articulated specimen of the enigmatic lizard *Bellairsia* found so far, enabled the authors to investigate the animal's evolutionary relationships to other reptiles for the first time, using an approach called phylogenetic morphological analysis. But before they could begin this assessment, Tałanda *et al.* had to check a preassembled list of hundreds of morphological characters describing features of bones that would serve as input data for their analyses.

Squamates are astonishingly diverse, with thousands of species adapted to a large array of environments. However, little is known about the initial stages in the evolution of this group, and fossils that record the transition

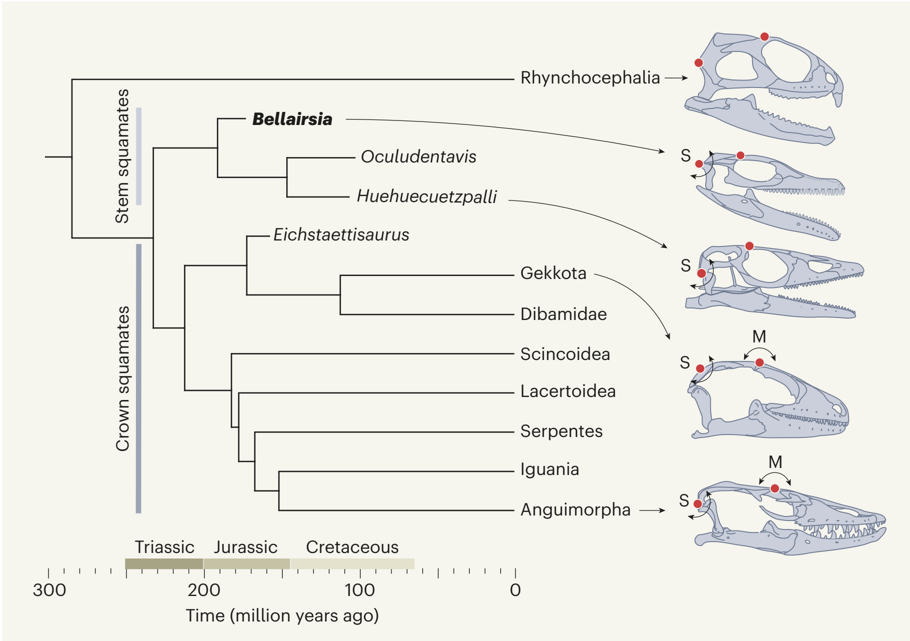

Figure 1 | The fossil lizard *Bellairsia*. Tałanda *et al.*[1] report the discovery of a 167-million-year-old fossil of *Bellairsia*. This specimen from the Jurassic period sheds light on previously unknown anatomical features of the species, which is part of the group of reptiles called squamates (which includes lizards and snakes). The closest relatives to squamates on the evolutionary tree are the rhynchocephalians. *Bellairsia* is the oldest known stem squamate – an extinct form that is related to, but outside, crown squamates, which is the group that contains all living forms of squamates. One question of interest when investigating squamate evolution is whether a species had the ability to rotate certain bones in the head relative to other bones. One type of such movement is called streptostyly (S), whereas movement of certain other structures is called mesokinesis (M). Red circles indicate the axes around which these rotations would occur, and if no arrows for rotations are shown, the species lacked the corresponding type of movement. The analysis of *Bellairsia* reveals that streptostyly was an early hallmark of squamates.

from primitive (ancestral-like) to advanced (modern-like) forms are extremely rare.

Tałanda *et al.* present evidence that *Bellairsia* represents a milestone in the evolutionary history of squamates. The specimen is a stem squamate – an extinct form that is closely related to, but just outside, the group that contains all living forms of squamates. It thus provides a snapshot during a key period in squamate evolution. As the authors note, there is robust evidence for this assignment of *Bellairsia* as a stem squamate, regardless of the type of analysis or data set used. Although other fossil forms, such as *Huehuecuetzpalli* and, with less certainty, *Oculudentavis* from the boundary between the Early and Late Cretaceous periods (about 100 million years ago), are suggested to represent a similar position to *Bellairsia* in the tree of life[3,4], those fossils were recovered from deposits more than 60 million years younger than the fossil samples analysed by Tałanda and colleagues.

Bellairsia is thus expected to be a more reliable example of a primitive squamate because it had comparatively less time to diverge from the original form of the ancestral squamate. However, it is much younger than the age of the split between squamates and their closest relatives (the rhynchocephalians), which occurred at least 240 million years ago[5].

Crucially, *Bellairsia* presents a mosaic of features associated with primitive and advanced squamates, and shows which sets of characteristics were established initially, and which were acquired subsequently during evolution. For instance, *Bellairsia* shares with modern squamates some of the traits related to a feature called cranial kinesis – the ability of the skull bones to move relative to each other. The quadrate bone, which serves as a joint between the jawbone and the cranium, would have been mobile, involving a type of movement termed streptostyly that is characteristic of most squamates, but not shared by the closely related rhynchocephalians (Fig. 1), which instead have what are termed akinetic skulls. Contacts between specific bones in the roof of the mouth (palate) and the cranium suggest, however, that a different type of movement called mesokinesis, which is widespread among advanced squamates, and refers to the mobility of the snout relative to the rest of the cranium, was not yet developed in *Bellairsia* (Fig. 1). The presence in *Bellairsia* of small elements known as intercentra between all the vertebrae, instead of only in the neck as occurs in most modern squamates, and of a particular mode of vertebral articulation called amphicoely, both represent further, presumably ancestral, traits.

The finding that an early squamate such as *Bellairsia* has certain typical squamate features related to the braincase, the pectoral girdle (bones that connect the forelimb to the body) and the quadrate bone suggests that these characteristics evolved earlier than did traits of the vertebrae or palate. Moreover, some of these ancestral traits shared by *Bellairsia* and other stem squamates are also found in geckoes, supporting a nearby (basal) position for the latter in the squamate tree, consistent with the results of studies using molecular data[6].

Tałanda and colleagues' findings will contribute to a renewed interest in small Jurassic vertebrate fossils, which are usually eclipsed by better-known Cretaceous specimens. They reveal the key role of Jurassic squamates in forging the success of this group, and support evidence from, for example, studies of the fossil record[7] or evolutionary trends at a large scale[8]. Moreover, the authors' finding emphasizes the transitional nature of Middle Jurassic faunas, revealing a mixture of primitive and advanced forms, and being consistent with the results of previous studies of squamates[9–11] and other small vertebrates such as amphibians and mammals[11,12]. The discovery of an articulated squamate at such an old locality is excellent news, because it opens up the possibility of finding complete specimens of other contemporary species from the time of *Bellairsia* that might represent the oldest-known representatives of their own lineages.

The results confirm Skye as a place of interest for investigating the early evolution of squamates. By providing insights into *Bellairsia*, the research contributes to efforts to understand the complex ecosystem that hosted these lizards, in what is arguably one of the most crucial known Jurassic localities of small vertebrates in the world.

Arnau Bolet is at Institut Català de Paleontologia Miquel Crusafont, Autonomous University of Barcelona, Cerdanyola del Vallès E08193, Spain, and in the School of Earth Sciences, University of Bristol, Bristol, UK.
e-mail: arnau.bolet@icp.cat

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