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Palaeontology

A colourful view of the origin of dinosaur feathers

Michael J. Benton

Birds and their dinosaur ancestors had feathers, and now it seems that a distantly related group called pterosaurs had them, too. The finding extends the origins of feathers back to long before birds evolved, and sheds light on their role. **See p.684**

In a simple world, an easy classification rule is that birds have feathers, mammals have hair and reptiles have scales, as did dinosaurs. However, the world is not necessarily simple, and it has been known for more than 25 years that at least some dinosaurs had feathers[1]. Previously, it was suggested[2] that flying creatures called pterosaurs – extinct distant relatives of birds and dinosaurs – also had feathers, but that idea was controversial[3]. On page 684, Cincotta *et al.*[4] confirm that pterosaurs possessed feathers, and also report that these feathers and their surrounding skin were coloured, perhaps providing signalling cues to other individuals of their kind.

Pterosaurs include more than 100 species of leathery-winged flying reptile. They are close relatives of, but clearly distinct from, dinosaurs. Pterosaurs and dinosaurs are preserved in the fossil record from roughly 230 million or 220 million years ago to 66 million years ago, a time frame that spans from part of the Late Triassic epoch to the mass extinction at the end of the Cretaceous period. Pterosaurs had large heads (Fig. 1) with sharp snouts, long necks, small bodies, tails of varying lengths and large wings made from a skin membrane that extended behind a 'leading edge' comprising the arm bones and a very long fourth finger. From the time of the early discoveries about these creatures, palaeontologists learnt that pterosaurs' bodies were covered in a 'fuzz' of short, whisker-like structures, which almost certainly provided heat insulation[5]. But was this pterosaur fluff composed of feathers?

Cincotta and colleagues describe the presence of diverse monofilaments (simple single-stranded whiskers) and branching feathers in the pterosaur *Tupandactylus*, in a fossil found in the Early Cretaceous period of Brazil (113 million years ago). Proposed fossil feathers have sometimes been rejected as being instead pieces of shredded skin or other tissue, overlapping monofilaments or degraded structures of some kind[3]. However, the detail of the regular branching in these structures inserted in the skin provides support for their identification as feathers.

Moreover, the feathers contain structures called melanosomes – capsules in feathers or hairs in which the pigment melanin resides. In modern birds and mammals, many of the dominant colours of feathers and hair come from a limited range of chemically distinct forms of melanin, mainly comprising eumelanin, which gives rise to black, brown, grey and blond colours, and phaeomelanin, which produces ginger colours. Melanin also occurs in the skin and in many internal organs, so it is important to be sure that the melanosomes are truly inside the feathers, not next to them. In this case, the feather melanosomes are definitely impressed into the tissues that represent the original keratin structural component of the feather.

Cincotta *et al.* report tissue-specific melanosome geometries – distinctive shapes of individual melanosomes and characteristic packing arrangements – in both feathers and skin tissues of the fossils, and these geometries indicate patchy distributions of colour. *Tupandactylus* was a large animal, with an estimated wingspan of 5 metres. It had a lightweight but huge head, with toothless jaws and two long, slender, bony rods, like the sail-supporting masts and spars of a sailing ship: one extending straight back and the other forming a near-vertical leading edge. In life, these spars supported a skin membrane that was covered with patchy coloured skin that, in turn, bore a short fuzz of coloured feathers.

The various species of *Tupandactylus* and their relatives had differently shaped crests (the structures built from skin stretched over the bony spars), each bearing irregular, large spots of colour – these crests are generally interpreted[6] to have been for signalling between individuals. Perhaps they were used

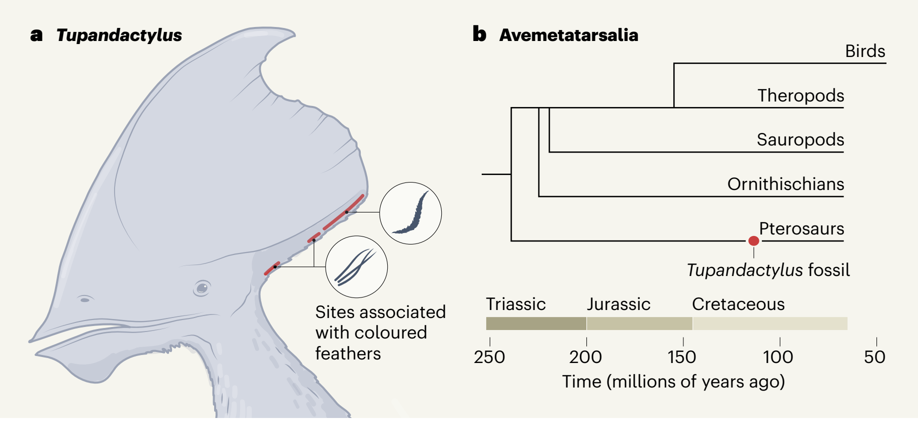

Figure 1 | Coloured feathers evolved early. a, Cincotta *et al.*[4] analysed a 113-million-year-old fossil of *Tupandactylus* – a species of flying vertebrate called a pterosaur. Pterosaurs and dinosaurs (theropods, sauropods and ornithischians) became extinct at the end of the Cretaceous period (66 million years ago). The authors report that the animal's head had coloured feathers – including both whisker-like monofilaments and branched feathers. The feathers contained capsules called melanosomes (not shown), which harbour the pigment melanin. The specific feather colour(s) are unknown. The colouring might have aided signalling between pterosaurs during mating displays. A complete head is shown, although the fossil is of a partial head. **b**, This discovery, along with other findings, might mean that coloured feathers evolved in the Triassic epoch, when the clade Avemetatarsalia, which includes pterosaurs, birds and dinosaurs, originated around 250 million years ago[10].

in pre-mating rituals, just as certain birds use colourful tail fans, wings and head crests to attract mates. Communication was also suggested as the function of the colourfully patterned feathers on the tails, wings and heads of some dinosaurs[6–8]. Modern birds are renowned for the diversity and complexity of their colourful displays, and for the role of these aspects of sexual selection in bird evolution, and the same might be true for a wide array of extinct animals, including dinosaurs and pterosaurs.

> **“Until now, much of the discussion about the origins of feathers has focused on their use in flight.”**

A key conclusion from Cincotta and colleagues’ work is that feathers, and all the complex abilities they offer both for insulation and signalling, originated once, at the origin of the clade Avemetatarsalia, which includes dinosaurs, birds and pterosaurs. It is possible that feathers evolved independently in several groups of dinosaurs as well as in pterosaurs, but the shared structural complexity of the pigments, and the inferred shared genomic heritage and shared pattern of developmental stages of these organisms, make a single point of origin more likely[4,9].

If so, this point of origin was probably in the Early Triassic, some 250 million years ago (on the basis of the age of the earliest-known avemetatarsalian fossils[10]). A series of discoveries over the past 25 years, including the study by Cincotta and colleagues, has therefore now shifted the origin of feathers to 100 million years earlier than was originally thought on the basis of the discovery of the earliest-known bird fossil, that of *Archaeopteryx*[11], which lived in Germany around 150 million years ago. Until now, much of the discussion about the origins of feathers has focused on their use in flight — an adaptation that arose in dinosaurs called theropods during the Middle to Late Jurassic epochs (about 165 million years ago)[5]. This new evidence will probably lead to a refocusing on the capacity for insulation that feathers provide as being, presumably, the main reason for their development, followed by their use for signalling.

The presence of feathers for insulation in the Avemetatarsalia suggests that the ancestors of pterosaurs and dinosaurs, and ultimately of birds, were warm-blooded to some degree, and lived faster lives than many of the other reptiles of their day — having the capacity for more-sustained activity throughout the day and the ability to run fast for longer. The time window of the origin of feathers, in the Early Triassic, coincides with the recovery of life from the end-Permian mass extinction, during which more than 90% of species became extinct on land and in the oceans. The reptiles ancestral to mammals, called synapsids, were already walking high on their limbs, were warm-blooded to some extent and perhaps had hair. I have previously suggested[12] that this period could mark a crucial time of arms races between synapsids and avemetatarsalians, each competing with the other as herbivores and as carnivores, and establishing the roots of a new kind of physiology at the same time.

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Polymer chemistry

Tailor-made enzymes for plastic recycling

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Waste streams of the plastic poly(ethylene terephthalate) that can be recycled into material suitable for food packaging are limited, creating a shortfall of feedstocks. An enzyme has been discovered that widens the feedstock options. **See p.662**

Plastics are exceptionally useful materials for packaging and all kinds of consumer items, but poorly managed plastic waste contributes to land and ocean pollution. This problem can, in principle, be prevented by recycling (Fig. 1). However, many plastic products were not designed for mechanical recycling, which involves melting and reprocessing, and therefore produces lower-quality material than the original plastic.

Items that are made predominantly from certain polymers, such as the widely used poly(ethylene terephthalate) (PET), can be converted back into the molecular building blocks (monomers) from which the polymers were made. The monomers can then be purified and repolymerized to make new plastics, a form of ‘closed-loop’ recycling. Standard chemical depolymerization processes are energy intensive and require large amounts of bases and acids, and are therefore not economically or ecologically viable. A potential solution is to use enzymes, but the lack of enzymes that have suitable activity for industrial-scale plastic depolymerization has hindered the development of this recycling strategy. On page 662, Lu *et al.*[1] report an engineered variant of an enzyme that brings closed-loop recycling nearer for commonly used PET-based products that were not designed for mechanical recycling.

A wide variety of packaging is made from PET, such as trays, tubs, cups and blister packs, and the demand for transparent, food-grade recycled PET (rPET), in particular, has risen greatly over the past two decades[2]. The highest-quality rPET is made from drinks bottles collected through deposit-refund systems, because these bottles are designed for recycling, and because the collection method precludes sorting mistakes. The number of countries using deposit-refund systems is growing steadily, boosting the amount of high-quality rPET that is produced. Even so, the market for PET drinks bottles is relatively small, and cannot supply sufficient material for the much larger PET-packaging market. Moreover, the shortage of collected and sorted PET bottles has driven up the cost of this feedstock enormously.

It is therefore essential for non-bottle PET to be collected and recycled into food-grade, transparent rPET. Various approaches have been adopted to achieve the required quality of material. Some recycling companies accept trays that have been specifically designed for recycling — that is, trays that do not contain components made from other polymers. Others have developed chemical recycling processes involving depolymerization,