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Palaeontology

The changing face of birds from the age of dinosaurs

Daniel J. Field

The fossil record traces the origin of the modern bird skull as birds evolved from their dinosaurian ancestors. Now the discovery of a bizarre fossil reveals a surprising diversion during this process of facial transformation. **See p.272**

As living dinosaurs, birds are the product of a long and complex evolutionary history that has given rise to more than 11,000 living species[1]. The past decade has witnessed a surge of interest in the evolution of the avian skull – a structure that is hugely variable across the diversity of living birds[2]. However, our ability to test hypotheses of how and when key transformations of the bird skull took place is limited if we can't incorporate fossils into evolutionary models. On page 272, O'Connor *et al.*[3] report a stunning fossil-bird discovery from the age of the dinosaurs that reminds us of the crucial value of fossils for casting light on unexpected complexities in avian evolutionary history.

This striking addition to the aviary of the Mesozoic era is between 72 million and 66 million years old (corresponding to the latest stage of the Cretaceous period). It comes from Madagascar, and is named *Falcatakely forsterae,* which roughly translates as Forster's small scythe beak. The name references the distinctive shape of the fossil's bill and honours Catherine Forster's numerous contributions to vertebrate palaeontology in Madagascar. The specimen is small (less than 9 centimetres long) and delicate (paper thin in places), yet the stunning bone preservation provides a spectacular look at this ancient creature's anatomy.

Although the fossil consists of only the front half of a skull, it's clear that *Falcatakely* is more than just a pretty face. The skull is utterly bizarre, characterized by a deep and elongated snout (Fig. 1) unlike those seen in any other Mesozoic birds. The skull's architecture becomes even weirder. The very tip of its snout has one small preserved tooth (the tip possibly had more teeth that were not preserved); however, there are clearly no teeth anywhere else along its jaws. By contrast, the closest relatives of modern birds from the time of the dinosaurs show the opposite pattern, with teeth found throughout the jaws, but none at the tip of the beak (Fig. 1)[4]. These features give the skull of *Falcatakely* an almost comical profile – imagine a creature resembling a tiny, buck-toothed toucan flitting from branch to branch, occasionally glancing down at Madagascar's formidable Late Cretaceous inhabitants, which included equally bizarre mammals[5] and giant predatory dinosaurs[6]. Despite the present-day catalogue of approximately 200 Mesozoic bird species from around the world[7], ranging in age from about 150 million to 66 million years old, none has a skull resembling anything like that of *Falcatakely*. Its discovery reveals a skull shape previously unknown for any bird from the age of the dinosaurs.

The exceptional degree of preservation of *Falcatakely* enabled the authors to make other astonishing findings. Imaging using a method called high-resolution microcomputed tomography enabled them to digitally 'extract' the fragile skull bones from the surrounding rock. O'Connor and colleagues could then reassemble the delicate components of the bill, including elements such as the paper-thin palate bones, which are rarely found preserved, into a compelling 3D model (see Supplementary Videos 1–8 of ref. 3).

Studying the palate, the authors spotted a surprising bone called the ectopterygoid. This is absent in living birds, but is a component of the palate of non-avian dinosaurs and early bird-like forms, such as the iconic early birds *Archaeopteryx* and *Sapeornis*[8]. However, on the basis of detailed analyses, O'Connor *et al.* infer that *Falcatakely* belongs to a group of Mesozoic 'pre-modern' birds called Enantiornithes

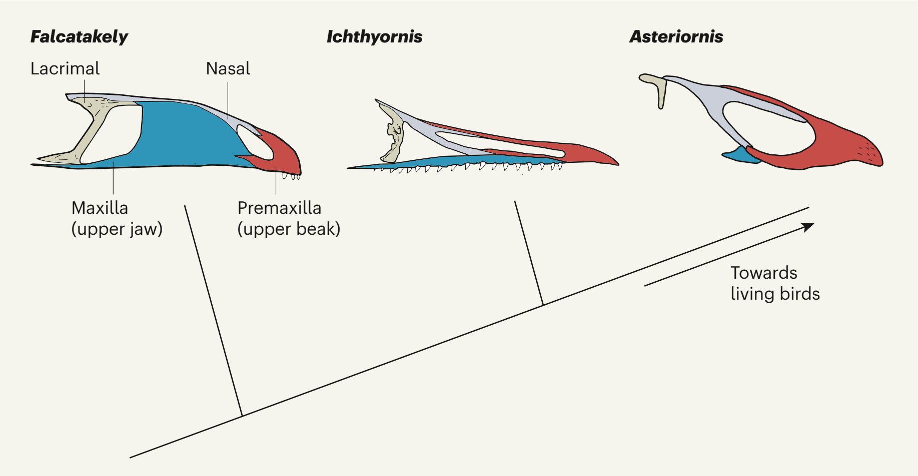

Figure 1 | The evolution of ancient bird skulls. Discoveries of bird skulls from the Mesozoic era (the age of the dinosaurs) have revealed both how the skull of modern birds arose and the surprising variability of these ancient skulls (as illustrated by these fossils, reported between 2018 and 2020). O'Connor *et al.*[3] present their discovery of the skull of a bird specimen they name *Falcatakely forsterae*, which shows an unusually deep and elongated snout, with teeth (at least one tooth and possibly more) positioned only at the very tip of the upper jaw in a skull region called the premaxilla. Like other distant relatives of modern birds, such as non-avian dinosaurs, the upper jaw of *Falcatakely* consists mainly of a region called the maxilla. Closer relatives of modern birds, such as *Ichthyornis*[4], had teeth throughout the jaws, except at the tip, and retained the ancestrally large maxilla. Early modern birds, including *Asteriornis* (an ancient relative of chickens and ducks)[13], lost their teeth completely, and had upper jaws dominated by the premaxilla. Nasal bones are shown in grey and lacrimal bones (inferred for *Asteriornis*) are in beige. (Figure adapted from Fig. 2 of ref. 3, Fig. 3 of ref. 4 and Fig. 1 of ref. 13.)

(a name that means 'opposite birds', in reference to their atypical shoulder-joint articulations), which occupy a branch of the dinosaur family tree that is much closer to that of modern birds than the branches occupied by either *Archaeopteryx* or *Sapeornis*. The presence of an ectopterygoid in Enantiornithes has been suggested previously[9], but this identification has been questioned[10]. Thus, the detection of an ectopterygoid in *Falcatakely* either shows that this ancestral component of the palate was indeed retained in Enantiornithes (at a relatively late stage in avian evolutionary history), or challenges the identification of *Falcatakely* as a member of Enantiornithes, suggesting instead that it belongs on a deeper branch of the family tree of Mesozoic birds.

Although it is impossible to decide definitively between these two options without access to further fossil material, O'Connor *et al.* grapple with this uncertainty to an impressively thorough degree, showing that *Falcatakely* nests with Enantiornithes in evolutionary trees constructed under a range of alternative analytical approaches. Moreover, the identification of *Falcatakely* as a member of Enantiornithes makes sense in light of the previous identification of fragmentary bones assigned to Enantiornithes from the same Madagascan fossil locality[11]. Nonetheless, some research has indicated that family-tree reconstructions of dinosaurs can return conflicting results when skulls, instead of complete skeletons, are analysed[12]. This lack of certainty is all the more reason for the team to continue its productive fieldwork in the hope of discovering more-complete material.

Modern birds originated in the Late Cretaceous[13], and it has become increasingly apparent that the final 20 million years of the age of the dinosaurs (86 million to 66 million years ago) was a pivotal time in avian evolutionary history. The discovery of *Falcatakely* shows us that the importance of this window in time for bird evolution extends well beyond the origin of modern birds. Apparently, 'pre-modern' bird lineages such as Enantiornithes were still experimenting with bold new forms — and possibly previously unfilled ecological niches — well into the terminal stages of the Cretaceous.

The pre-modern birds were wiped out in the end-Cretaceous mass extinction event, along with all other dinosaurs, apart from modern birds[14]. Considering the impressive diversity and global distribution of Enantiornithes in the Late Cretaceous, determining why they disappeared in that mass extinction, whereas the earliest modern-bird lineages survived, remains one of the greatest mysteries in avian evolutionary history. The answers to such questions, much like the unexpected anatomy of creatures such as *Falcatakely*, can be revealed only by evidence from the fossil record. So, let's keep digging.

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Particle physics

How protons interact with their exotic siblings

Manuel Lorenz

The nuclear forces that act on short-lived subatomic particles have been hard to study. This problem has now been solved by smashing high-energy protons together and measuring the momenta of the unstable particles produced. **See p.232**

On page 232, the ALICE Collaboration[1] reports that data from high-energy collisions between protons can be used to investigate the little-understood nuclear forces between protons and subatomic particles called hyperons. The measurements have comparable precision to state-of-the-art numerical calculations of the forces, thereby allowing conclusive quantitative comparisons of experimental data with theory. Accurate knowledge of these forces is needed for various aspects of physics research, for example in efforts to understand the stability of neutron stars.

The nuclear force between neutrons and protons (which are known collectively as nucleons) is a residual effect of the strong interaction that acts between their elementary constituents (quarks and gluons). First-principles calculations of the nuclear force have been challenging because of the peculiarities of the strong interaction. Our knowledge of this force is, therefore, based largely on simplified models and theories[2], guided by experimental data[3]. The strong interaction between hadrons (subatomic particles, such as nucleons, that consist of two or more quarks bound together by the strong interaction) at low energies is therefore often referred to as the final frontier of the standard model of particle physics.

The interaction between nucleons has been measured with high accuracy[3], but the interaction of nucleons with their heavier siblings, the hyperons, is less well assessed. Hyperons consist of three quarks, at least one of which must be a type (flavour) known as a strange quark; the other quarks can be up or down, the two lightest quark flavours. Hyperons are not present in the everyday matter that surrounds us on Earth, but — depending on their interactions with nucleons — might affect the compressibility of nuclear matter at high densities. This means they could be relevant to the stability of neutron stars[4]. Precise knowledge of hyperon–nucleon interactions is therefore of great importance not only for nuclear physics, but also for astrophysics. However, measurements of these interactions are difficult to make in conventional experiments involving direct particle collisions in accelerators, because hyperons are short-lived (their lifetimes are about 10^{-10} s; ref. 5) and fly only a few centimetres, on average, before they decay.

The ALICE Collaboration now reports that proton–hyperon interactions can be investigated using high-energy collisions between protons carried out at the Large Hadron Collider (LHC) at CERN, Europe's particle physics laboratory near Geneva, Switzerland. The technique depends on measurements of correlations between the momenta of protons and hyperons produced in the collisions.

The process studied in the experiments involves three steps (Fig. 1). First, protons are collided at extremely high energies, taking advantage of the fact that the LHC produces higher collision energies than any other accelerator. Second, hadrons are emitted