Origin of Birds: Decade-Long Efforts and Evidence from China

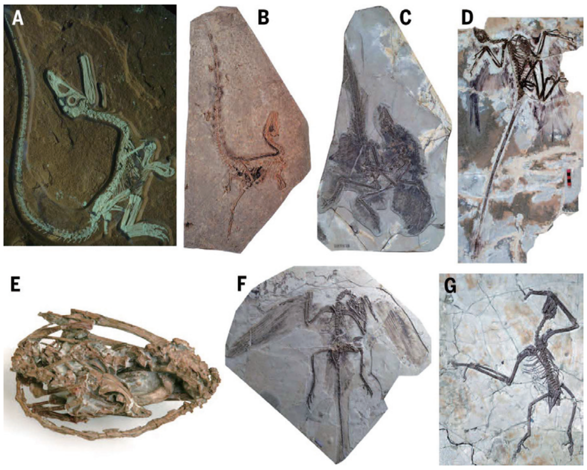
By CHEN Pingfu[1], ZHAO Guoxing[2] & PENG Guoqing[3]

In its 2014 version of top 10 ground-breaking discoveries and achievements released on December 19, *Science*, the world-leading journal included the transition from dinosaurs to birds in its annual selection, noting that a series of papers detailed how certain dinosaurian lineages developed small, lightweight body features, which have enabled them to evolve into birds and gain the ability to fly.

The dinosaur-bird transition, now evaluated as one of the best documented ever in the history of paleontology, took paleontologists decades to understand, however. Accumulated evidence eventually helped scientists figure out the mode and tempo of this spectacular evolutionary transition. Their studies of fossils, primarily from China, and the latest results from DNA analysis have unveiled how ancient dinosaurs evolved into the small, lightweight bodies that gave rise to modern birds.

The origin of birds is one of the most enduring and dramatic evolutionary debates. The hypothesis that the primarily small-sized birds could have descended from a theropod dinosaur group including the gigantic *Tyrannosaurus rex* has been supported by strong fossil evidence, but until recently, several important issues remained unresolved, including the origins of feathers and flight, the "temporal paradox" (the coelurosaurian theropods occurred too late in the fossil record to be ancestral to the Jurassic bird *Archaeopteryx*), and supposed homological incongruities (*e.g.*, the suggested homologies of three fingers in tetanuran theropods are different from those of living birds). Fortunately and remarkably, recent discoveries of spectacular dinosaur fossils from China and elsewhere provided new information to address these issues.

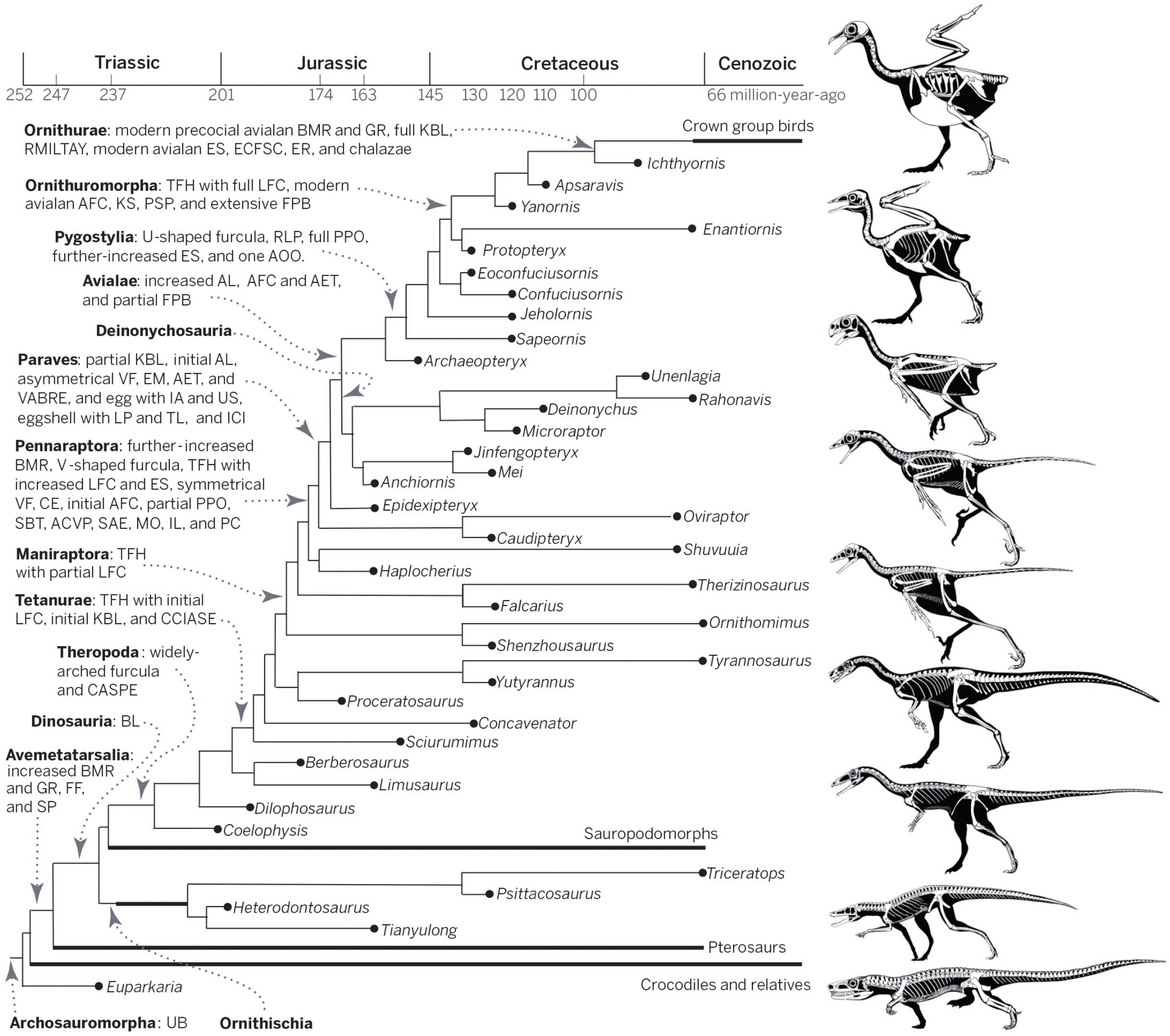
In a paper published on 2014 December 12 in *Science*, Drs. XU Xing and ZHOU Zhonghe from the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), CAS and their collaborators reviewed recent discoveries of spectacular bird/dinosaur fossils, and demonstrated that distinctive bird characteristics such as feathers, flight, endothermic physiology, unique strategies for reproduction and growth, and a novel pulmonary system originated among Mesozoic terrestrial dinosaurs. They pointed out that the iconic features of extant birds for the most part evolved in a gradual and stepwise fashion throughout archosaur evolution, with occasional bursts of morphological novelty at certain stages particularly close to the origin of birds, resulting in an unavoidable complex, mosaic evolutionary distribution of major bird characteristics on the theropod tree. The study points to recent dinosaur fossil discoveries in China as providing more proof supporting the theory that birds descended from theropod dinosaurs.



Selected recently discovered transitional forms of theropods and early birds. *Sciurumimus* (A), *Sinosauropteryx* (B), *Anchiornis* (C), *Microraptor* (D), *Mei* (E), *Jeholornis* (F), and *Sapeornis* (G). (Adapted from Xu *et al*., 2014)

Birds owe their success to their flight, wings and feathers. Numerous feathered dinosaurs and primitive birds discovered

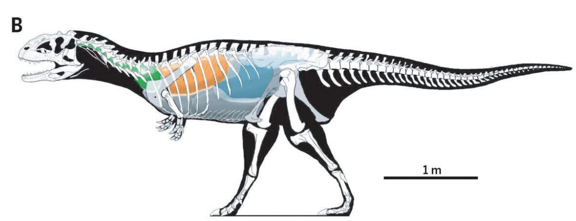
1. Institute of Vertebrate Paleontology and Paleoanthropology, CAS, Beijing 100044;
2. Ordos Museum, Ordos 017200, China;
3. Harbin Yao Qing Animal Fossils Repair Co. Ltd, Haerbin 150000, China.



The evolution of major characteristics along the birdline. (Adapted from Xu *et al*., 2014)

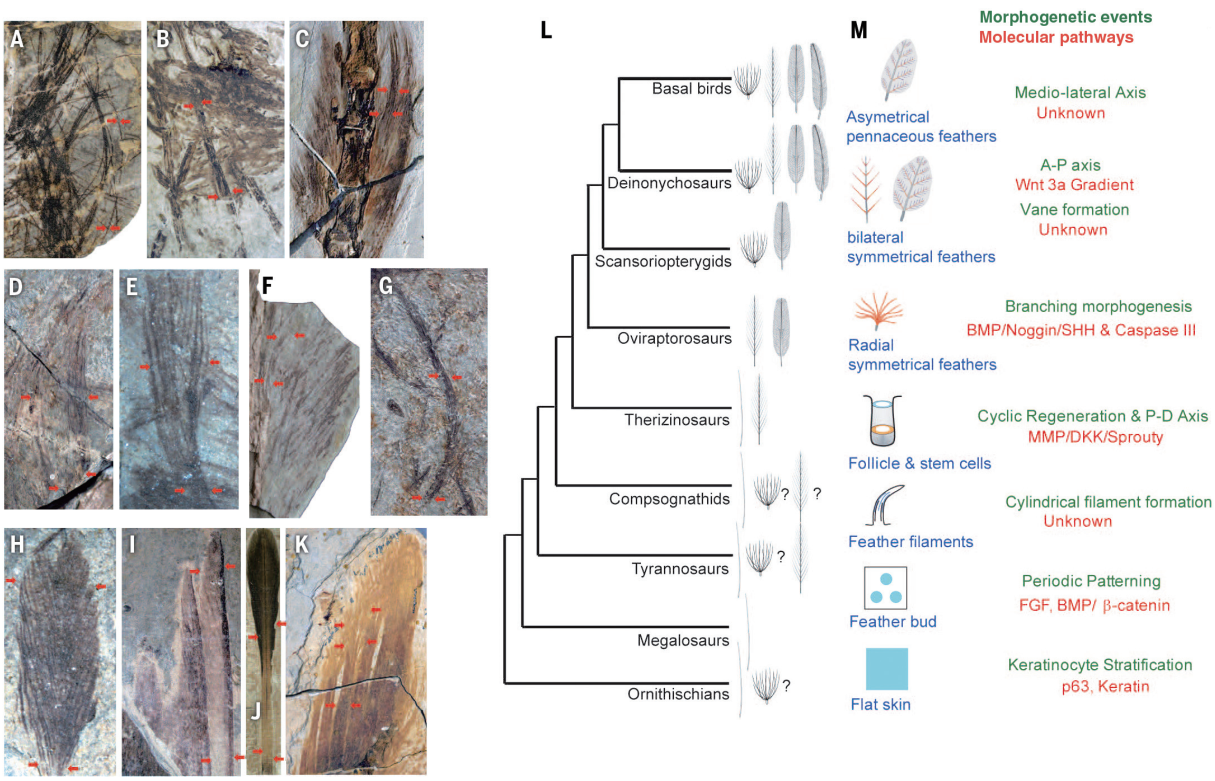
in China in the past two decades have made great contributions to research on the origin of birds and related questions in particular. IVPP researchers and their collaborators provided strong evidence for the idea that birds were derived from dinosaurs, which was first championed by Huxley and later by Nopcsa and Ostrom.

Back in 2003, Dr. XU Xing and his collaborators reported a new dromaeosaurid species, *Microraptor gui*, from the Jehol Group of western Liaoning, China. The article published on January 23 in *Nature* provided new evidence suggesting that basal dromaeosaurid dinosaurs were four-winged animals and probably could glide, representing an intermediate stage towards the active, flapping-flight stage. The new discovery confirmed the predictions of early hypotheses that proavians passed through a tetrapteryx stage.



Reconstruction of pulmonary components [cervical air-sac system (green), lung (orange), and abdominal air-sac system (blue)] in the theropod *Majungatholus* (From Xu *et al*., 2014)

In 2009, Dr. XU Xing and his team reported a maniraptoran dinosaur, *Anchiornis huxleyi*, which is now considered the oldest bird-like dinosaur to date. This new finding, published in the September 24 issue of the journal *Nature*, suggests that dinosaurs with flight feathers might have appeared at least about 160 million years ago and birds' direct ancestors are probably four-winged animals. *Anchiornis* lived about 30 million years before the feathered dinosaur



The morphogenesis and evolution of feathers in dinosaurs. (Adapted from Xu *et al*., 2014)

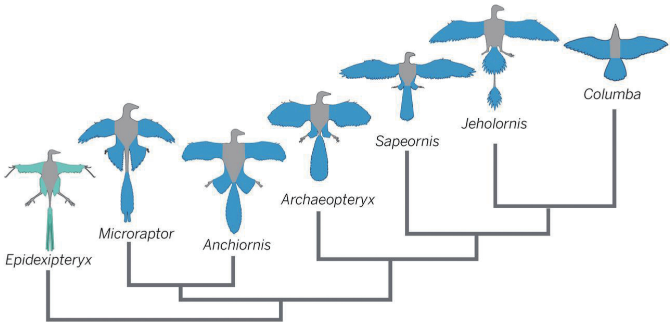
Microraptor and about 5 million years before the oldest known bird, *Archaeopteryx*, the researchers said. This earlier emergence of feathered dinosaurs weakens the claims that bird-like dinosaurs appear too late in the fossil record to be true ancestors of birds.

In 2010, Dr. ZHANG Fucheng of the IVPP and his collaborators found two types of melanosomes, the sausage-shaped eumelanosomes and the spherical phaeomelanosomes, in the tiny feathers or bristles on some primitive birds and feathered dinosaurs from the Jehol Biota, as reported in *Nature* on January 28. Given that in extant birds melanosomes are only found in the developing feathers instead of the hypodermic fibers, this discovery hints that some theropod dinosaurs did have colorful feathers, and confirms that the "feather-like integuments” found in some fossil dinosaurs are of the same origin as extant birds.

In 2012, Dr. XU Xing and his team described three specimens of a new tyrannosauroid, *Yutyrannus huali*, from a single quarry in Cretaceous beds in Liaoning Province in the April 05 issue of *Nature*, dramatically increasing the size range of dinosaurs for which we have definite evidence of feathers. Researchers estimated that an adult *Yutyrannus* would have been about 9 metres long and weighed about 1,400 kg, making it considerably smaller than its infamous relative *Tyrannosaurus rex* but some 40 times the weight of the largest feathered dinosaur previously known, *Beipiaosaurus*. It’s possible that feathers were much more widespread, at least among the meat-eating dinosaurs, than most scientists would have guessed even a few years before. Close examination of the earliest theropod dinosaurs suggests that feathers were initially developed for insulation, arranged in multiple layers to preserve heat, before their shape evolved for display and camouflage.

In an article published online on March 17 2013 in *Nature*, Dr. ZHOU Zhonghe and his team described three specimens of fossil bird from the Early Cretaceous Jehol Group, which preserved the remains of mature ovarian follicles in their abdominal cavity. This is the first discovery of preserved soft tissue of reproductive organs in a fossil tetrapod. The three fossils record a wide phylogenetic bracket within Aves, preserved in one specimen of the long boney-tailed bird *Jeholornis*, the second oldest and most primitive fossil bird (after *Archaeopteryx*), and two enantiornithines – a sister taxon to Ornithuromorpha, the group that includes living birds. Comparisons in ovarian morphology between *Jeholornis* and Enantiornithes reveal an evolutionary gradient from the non-avian dinosaurian condition towards that of modern birds.

According to a paper published on March 15 2013 in *Science*, Drs. XU Xing and ZHOU Zhonghe, and their collaborators described 11 specimens of different bird species that preserve exceptional integumentary structures associated with the hindlimb, and confirmed the presence of a four-



Airfoils of selected maniraptorans. Airfoils (in blue) of the basal dromaeosaur *Microraptor*, the basal troodontid *Anchiornis*, the basal birds *Archaeopteryx*, *Sapeornis*, and *Jeholornis*, and a modern pigeon. (Adapted from Xu *et al*., 2014)

winged condition in early birds. Their study demonstrates a distal-to-proximal reduction pattern for leg feathers in avialan evolution, and suggests that extensively scaled feet might have appeared secondarily at an early stage in ornithuromorph evolution.

It is widely accepted that birds are a subgroup of dinosaurs, but there used to be an apparent conflict: modern birds have been thought to possess only the middle three fingers (digits II-III-IV) of an idealized five-digit tetrapod hand based on embryological data, but their Mesozoic tetanuran dinosaur ancestors are considered to have the first three digits (I-II-III) based on fossil evidence. In a paper published on June 23, 2013 in the journal *Current Biology* (23), Dr. XU Xing, and his collaborators reviewed and compared several hypotheses that have been proposed to reconcile the digit homology paradox, and most importantly, discussed the developmental processes that may have contributed to shaping the evolution of the avian wing digits, helping us better understand the complexity of the evolution of avian wing digits.

Another controversial issue solved by Dr. XU Xing *et al*. was the homology of the "semilunate" carpal, an important structure linking dinosaurs and birds. In a study published online on Aug 13, 2014 in the journal of *Scientific Reports*, Dr. XU Xing and his colleagues described the morphology of some theropod wrists, demonstrating that the "semilunate" carpal is not formed by the same carpal elements in all theropods possessing this feature and that the involvement of the lateralmost distal carpal in forming the "semilunate" carpal of birds is an inheritance from their non-avian theropod ancestors. Optimization of relevant morphological features indicates that these features evolved in an incremental way and the "semilunate" structure underwent a lateral shift in position during theropod evolution, possibly as a result of selection for foldable wings in birds and their close theropod relatives.

The year 2014 witnessed several groups compiling and analyzing data on many dinosaur and early bird fossils as well as on extant birds, to see when other birdlike traits actually appeared. One study compared 850 morphological traits among 150 species; another measured the thickness of leg bones of 426 species. They discovered that the dinosaurs that ultimately gave rise to birds steadily got smaller and finer boned over time. Being smaller and lighter on the land of giants, with rapidly evolving anatomical adaptations, provided these bird ancestors with new ecological opportunities, such as the ability to climb trees, glide and fly. Ultimately, this evolutionary flexibility helped birds survive the deadly meteorite impact which killed off all their dinosaurian cousins.

"Paleontology in China has blossomed into a strong research enterprise during the last two decades, thanks to financial support from CAS, including the Strategic Priority Research Program, Fossil Excavation and Preparation Fund, and the Hundred-Talent Program. Special thanks should also be given to support from the National Natural Science Foundation of China as well as ministerial departments including the Ministry of Science and Technology of China, the Ministry of Land and Resources of China, and the National Bureau of Cultural Relics of China", said Dr. ZHOU Zhonghe, Director of the IVPP.

For more information please refer to:

Pennisi E., (2014) Runners-up, *Science*, 346: 1444–1449 [doi: 10.1126/science.346.6216.1444].

Xing Xu, Zhonghe Zhou, Robert Dudley, Susan Mackem, Cheng-Ming Chuong, Gregory M. Erickson, David J. Varricchio, (2014) An integrative approach to understanding bird origins, *Science*: 1253293 [doi:10.1126/science.1253293].

X. Xu, F. Han, Q. Zhao, (2014) Homologies and homeotic transformation of the theropod "semilunate" carpal, *Sci. Rep.*: 4, 6042 [doi: 10.1038/srep06042].

X. Zheng, J. O'Connor, F. Huchzermeyer, X. Wang, Y. Wang, M. Wang, Z. Zhou, (2013) Preservation of ovarian follicles reveals early evolution of avian reproductive behavior, *Nature* 495: 507–511 [doi:10.1038/nature11985].

X. Xu, S. Mackem, (2013) Tracing the evolution of avian wing digits, *Curr. Biol.*: 23, R538 [doi:10.1016/j.cub.2013.04.071].

X. Zheng, Z. Zhou, X. Wang, F. Zhang, X. Zhang, Y. Wang, G. Wei, S. Wang, X. Xu, (2013) Hind wings in basal birds and the evolution of leg feathers, *Science* 339: 1309–1312 [doi:10.1126/science.1228753].

Xing Xu, Kebai Wang, Ke Zhang, Qingyu Ma, Lida Xing, Corwin Sullivan, Dongyu Hu, Shuqing Cheng, Shuo Wang, (2012) A gigantic feathered dinosaur from the Lower Cretaceous of China, *Nature* 484: 92–95 [doi:10.1038/nature10906].

F. Zhang, S. L. Kearns, P. J. Orr, M. J. Benton, Z. Zhou, D. Johnson, X. Xu, X. Wang, (2010) Fossilized melanosomes and the colour of Cretaceous dinosaurs and birds, *Nature* 463: 1075–1078 [doi:10.1038/nature08740].

X. Xu, Z. Zhou, X. Wang, X. Kuang, F. Zhang, X. Du, (2003) Four-winged dinosaurs from China, *Nature* 421: 335–340 [doi:10.1038/nature10906]