Paleontologists are flocking to China, which has beefed up its support of the field to take advantage of troves of superbly preserved specimens

Exquisite Chinese Fossils Add New Pages to Book of Life

PALEONTOLOGY IN CHINA

This story concentrates on the exciting fossil finds coming out of China. It is followed by a look at the rising support for the field and the key people and institutions, the obstacles to progress, and the nature of foreign collaborations.

SIHETUN VILLAGE, CHINA—Zhou Zhonghe came back to China for the fossils. Gazing out at what had once been a region of shallow lakes rich in fish, birds, and dinosaurs, the 36-year-old Zhou knows there is no better place for an avian paleontologist to work than these rolling hills of farmland in northeastern China.

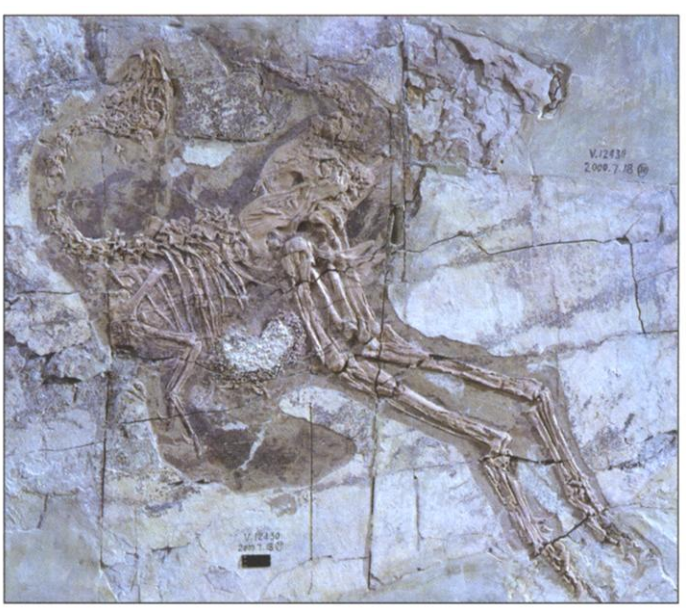
Six years ago, as a graduate student at the University of Kansas, Zhou was part of a team that first described a primitive, magpie-sized bird from China called *Confuciusornis*. Since returning to his homeland in 1999, Zhou has also worked on feathered dinosaurs from the same fossil beds here in western Liaoning Province. These discoveries may help end one of the most high-powered debates in paleontology—whether birds evolved from dinosaurs. Along with a profusion of other high-quality specimens in the region, they are also yielding a detailed picture of life 125 million years ago, during the Early Cretaceous. Says James Clark of George Washington University in Washington, D.C.: "It's one of the most exciting areas in the world right now for vertebrate fossils."

Liaoning is not the only paleontological hot spot in China. The Chengjiang formation in southwestern Yunnan Province boasts remarkably well-preserved fossils that are helping paleontologists document the Cambrian explosion of life some 530 million years ago. Chengjiang has already yielded creatures that are pushing back in time the appearance of key features of vertebrates, and it recently produced the world's oldest fish. Prizes like this have attracted massive interest.

Smaller sites all across China are also drawing paleontologists who hope to fill in missing chapters of the history of life. When Johnny Waters of the State University of West Georgia first saw the fossilized echinoderms that a Chinese colleague had brought to a meeting in the United Kingdom in 1991, his eyes nearly bugged out. He and colleagues Chris Maples and Gary Lane of Indiana University, Bloomington, immediately arranged to visit the remote site in the desert of northwestern China that is yielding beautifully preserved specimens from the late Devonian, a time 355 million years ago when echinoderms were thought to have suffered a massive extinction. Digging in the barren, windswept outcrop that makes up the Hongguleleng formation in Xinjiang, they discovered more species than had ever been collected from that time period. "It gives us a whole different look at the recovery from the Devonian mass extinction," says Doug Erwin of the Smithsonian Institution in Washington, D.C.

These and other findings have made China a Mecca for paleontologists. The country's complex geology gives it a uniquely diverse collection of fossils. Rising government support for the field is making it possible for Zhou and his colleagues to pursue these exciting opportunities, and an increasing number of collaborations is bringing in foreign scientists and resources. "This tremendous range of ages and environments is very exciting," says Philip Currie of the Royal Tyrrell Museum in Drumheller, Canada. "In areas where [North American paleontology] is weak, we can look for answers in China."

The influx of money and talent comes just as China has begun to embrace Western-style research practices, including a system of competitively awarded grants built upon bottom-up proposals. And the effect is already clear. "There are a number of fronts on which superbly preserved fossils are making a difference in the way we think about the history of life," says Andrew Knoll, a paleontologist at Harvard University.



Beautiful bones. Many fossils from Liaoning, like the dinosaur *Caudipteryx*, are well preserved.

CREDIT: Z. ZHOU

Earliest vertebrates

Competition is fever-pitched in Yunnan Province, where many teams are looking for the earliest vertebrates. Paleontologists have long believed that this group first appeared during the Cambrian explosion, when most of the body plans of modern animals were laid down. But the record is sparse, because Cambrian creatures were mostly soft-bodied and their parts don't preserve well. Indeed, until the mid-1990s, the record of fossil vertebrates went back only about 475 million years, when small, jawless fish with bony plates lived in the Ordovician. In the past few years, however, Yunnan's Chengjiang formation has extended that record by a startling 60 million years.

The formation, some 50 meters thick, contains extremely rich deposits of fossils and outcrops in sparsely vegetated hills that stretch for about 100 kilometers east to west. "You can find 20 specimens per day" in some places,

says Jin Yugan of the Nanjing Institute of Geology and Paleontology (NIGP), which has a team working on the beds. The rocks predate the Burgess Shale—a rich collection of Cambrian life preserved in Canada—perhaps by as much as 10 million years, putting them closer to the origin of vertebrates. "The closer you can get to that [point]," says Yu Xiaobo of Kean University in Union, New Jersey, "the more significant your material." The formation has been known for several decades, but it first drew major attention in 1995, when Chen Junyuan of NIGP argued that a 4-centimeter-long creature, *Yunnanozoon*, was a chordate, the group that includes vertebrates.

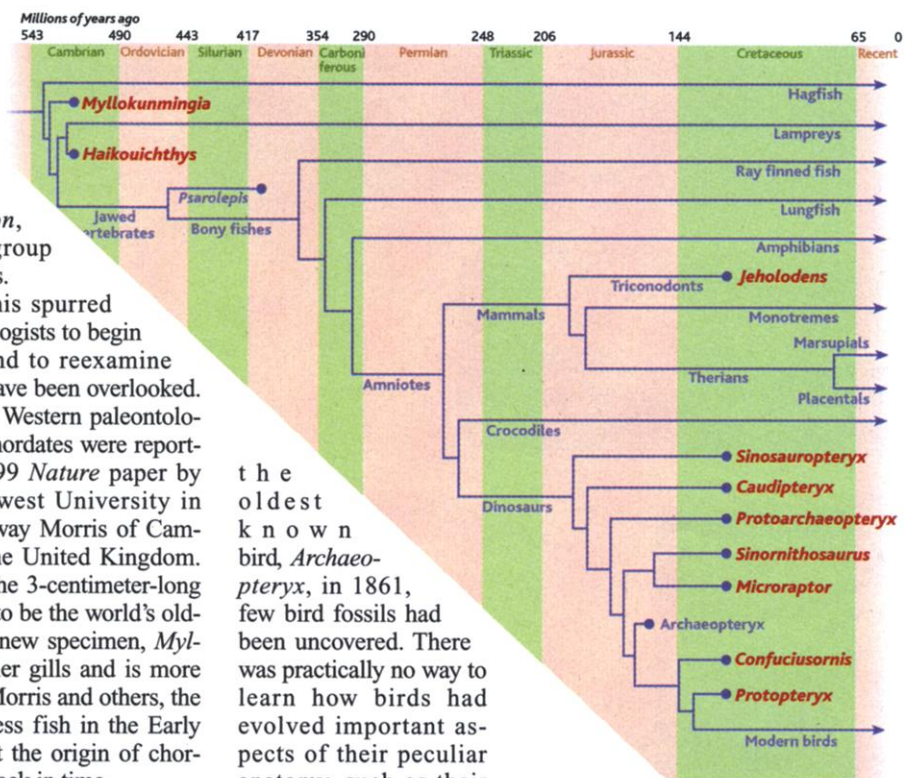
Discoveries like this spurred other Chinese paleontologists to begin digging for fossils and to reexamine specimens that might have been overlooked. The pace quickened as Western paleontologists joined in. More chordates were reported in a November 1999 *Nature* paper by Shu Degan of Northwest University in Xi'an and Simon Conway Morris of Cambridge University in the United Kingdom. At 530 million years, the 3-centimeter-long *Haikouichthys* appears to be the world's oldest fish, while another new specimen, *Myllokunmingia*, has simpler gills and is more primitive. To Conway Morris and others, the presence of these jawless fish in the Early Cambrian suggests that the origin of chordates lies even farther back in time.

Hoping to learn more, the Chinese government last year awarded $2.4 million over 5 years to eight teams of scientists from NIGP, the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) in Beijing, and several universities to further investigations at Chengjiang and Liaoning. "It's very strong support," says Sun Weiguo of NIGP. But the riches have also created tensions. At least five rival teams are already working in Chengjiang, and "there is no cooperation between the different groups," says Hou Xianguang of Yunnan University, who in 1984 discovered the first soft-bodied fossils at Chengjiang.

Flight and fight

All the same factors—ample money, competition, incredible enthusiasm, and important questions—are also visible some 3000 kilometers to the northeast in western Liaoning Province. The extensive rock layers of lake mud and volcanic ash bear evidence of feathered dinosaurs, primitive birds, and other rare animals entombed by occasional volcanic eruptions. Their rapid burial kept the skeletons intact—sometimes even including undigested lizards and mammals in the stomachs and unlaid eggs in the abdomen—and the fine sediment preserved impressions of skin and feathers. The region became world famous after primitive fossil birds were discovered in the mid-1990s at two sites near the town of Beipiao.

This was a breakthrough for avian paleontologists. Since the discovery of the oldest known bird, *Archaeopteryx*, in 1861, few bird fossils had been uncovered. There was practically no way to learn how birds had evolved important aspects of their peculiar anatomy, such as their keeled sternum to which their powerful flight muscles attach. In the last decade, a few finds have emerged from Mongolia, Spain, Argentina, and Madagascar. But these are dwarfed by the sheer number of fossil birds from China, making Liaoning the hottest spot in the world for fossil birds.



Fruitful. Chinese discoveries (in red) are filling in many branches of the vertebrate tree of life.

Pulled out of hillside quarries and eroding stream banks in dry farmland, the Chinese fossils point to a surprising diversity of birds in the early Cretaceous, the most recent of which, *Protopteryx*, was published last month (*Science*, 8 December 2000, p. 1955). The discoveries include several dozen taxa, some with an intriguing mix of primitive and advanced features. The birds shed light on the evolution of avian anatomy, such as the shoulder girdle, wing, and keeled sternum. "Now we have samples of an incredible mosaic of birds that give insight into how these morphological systems evolved," says avian biologist Rick Prum of the University of Kansas Natural History Museum in Lawrence.

The best known of these primitive birds, the magpie-sized *Confuciusornis*, was first described in 1995 by Hou Lianhai of IVPP, along with Zhou, Larry Martin of the University of Kansas, Lawrence, and Alan Feduccia, an ornithologist at the University of North Carolina, Chapel Hill. Unlike its scarce relative, *Archaeopteryx*, so many specimens of *Confuciusornis* have turned up that a paleontology museum outside Beipiao has cemented a dozen onto a wall for decoration. "For the first time we have an enormous sample of ancient birds," says Luis Chiappe of the Natural History Museum of Los Angeles County.

Chiappe says the surfeit will allow new lines of research, such as morphometric analysis to check for sexual dimorphism in the plumage and cross sections of bone tissue that might reveal how early birds like *Confuciusornis* grew. Cross sections are never allowed on rare specimens. Prum agrees: "The prospect of learning a lot about its biology is tremendous." Indeed, Zhou, who in 1999 returned to IVPP, is so eager to explore the incredible paleontological wealth buried in western Liaoning Province that, last fall alone, he made the 400-kilometer trip four times.

The extraordinary preservation of the Liaoning fossils—far superior to those almost anywhere in the world—has also made them key players in one of paleontology's most high-voltage debates. Most paleontologists believe that birds evolved from dinosaurs, because the two groups share many important skeletal features such as a wishbone and long arms. But feathers had always been considered the ultimate avian attribute. That's why signs of feathers on recently discovered Chinese dinosaur fossils have made such a stir.

The first hint that dinosaurs might have been feathered came at the annual meeting of the Society of Vertebrate Paleontology, in October 1996. In the hallways, Chen Peiji of NIGP showed photos of a small dinosaur, named *Sinosauropteryx*, that appeared to

CREDIT: ADAPTED FROM P. JANVIER, *NATURE* **402**, 21 (1999); Q. JI, *NATURE* **398**, 326 (1999); L. CHIAPPE, *BULL. AM. MUS. NAT. HIST.* **242**; X. XU, *NATURE* **408**, 705 (2000)

A Peek at China's Paleontological Bounty

China possesses an immense wealth of fossils. Its treasures range from some of the oldest known animals—such as the roughly 570-million-year-old Precambrian embryos of Guizhou Province—to 40-million-year-old early primates of the Eocene, and more recent finds as well.

For decades Chinese geologists have mapped the fossil-bearing rocks in their country and determined their ages to foster exploitation of the country's vast energy and mineral resources. Now that work is also beginning to pay big dividends in fossils that are helping to answer a wide range of evolutionary questions. It has already shed light on the origin of vertebrates and the nature of mass extinctions such as the one that marked the end of the Permian period.

The search spans the country, the third largest in the world, from the monsoon-drenched outcrops of southwestern Yunnan to the arid badlands of northwestern Xinjiang to the hills of northeastern Liaoning, with its famous feathered dinosaurs. This map illustrates some of the staggering array of well-preserved fossils that are attracting scientists from around the world.

For ages of geologic periods, see diagram on page 233.

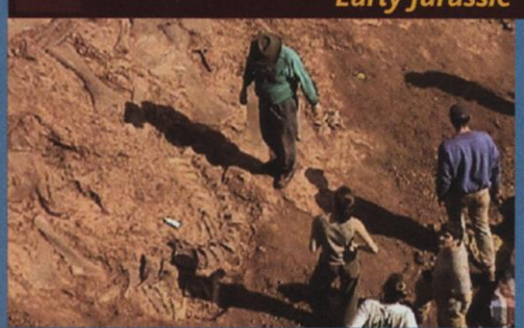
Northern Xinjiang
Late Devonian

Echinoderms not found outside of China have changed ideas about the group's recovery from a mass extinction.

Xinjiang Province
Late Jurassic and Early Cretaceous

The badlands of the Junggar Basin, like many parts of northwestern China, contain a rich diversity of Mesozoic fossils.

Yunnan Province
Early Jurassic



China has abundant collections of dinosaurs, like this quarry full of sauropods near Lufeng.

Yunnan Province
Early Cambrian

The chordate *Haikouichthys*, part of the Chengjiang fauna, may be as much as 10 million years older than the creatures found in the Burgess Shale. It's shedding new light on the Cambrian Explosion.

Yunnan Province
Early Devonian

A bizarre and very primitive fish called *Psarolepis* may be the earliest member of bony fishes.

C H I

PLATEAU OF TIBET

Map by Alex Tait/Equator Graphics, Inc.

CREDITS: (CLOCKWISE, BEGINNING TO THE RIGHT OF THE MAIN CAPTION) C. MAPLES; P. CHEN *ET AL.*, *NATURE* **391**,147 (1998); D. ERWIN; S. XIAO, *NATURE* **391**,553 (1998); S. CONWAY MORRIS.

SW Guizhou Province
Triassic

Complete skeletons of marine reptiles, such as thalattosaurs, may help solve problems in ocean biogeography.

Inner Mongolia
Cretaceous

Dinosaur eggs and nests, as well as turtles, crocodiles, and lizards, have been found around the Bayan Mandahu site.

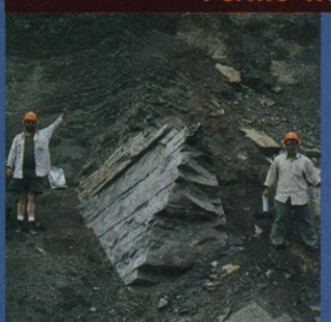
Western Liaoning Province
Early Cretaceous

The Jehol fauna boasts an array of spectacularly well-preserved fossils, such as *Sinosauropteryx*, a feathered dinosaur.

Southern Shanxi Province
Eocene

The 40-million-year-old "dawn monkey" *Eosimias* is the most primitive higher primate known. The mouse-sized fossil suggests that higher primates may have originated in Asia.

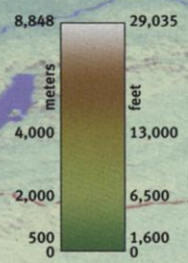
NW Zhejiang Province
Permo-Triassic



Outcrops across southern China, especially near Meishan, are helping to explain the greatest mass extinction ever.

Central Guizhou Province
Late Precambrian

Embryos preserved in the Doushantuo Formation may help identify some of the earliest known multicellular life.



GOBI

Yellow

Beijing

NA

Nanjing

Yangtze

Kunming

Hongshui

KEY

Dinosaurs, Turtles, Pterosaurs, Early vertebrates, Sponges, Bivalves, Cephalopods

Birds, Crocodiles, Fishes, Arthropods, Ammonoids, Foraminifera, Brachiopods

Mammals, Lizards, Marine reptiles, Echinoderms, Conodonts, Ostracods, Plants

contain impressions of fine bristles up to 4 centimeters long fringing its neck and spine. It wasn't clear whether the filaments were really feathers, however. Some paleontologists viewed them as transitional "protofeathers," while others dismissed the filaments as frayed bits of decaying tissue.

In June 1998, unambiguous feathers came to light. Ji Qiang, then director of the National Geological Museum, and his colleagues Currie, Mark Norell of the American Museum of Natural History in New York City, and Ji Shuan of the Geological Museum described two new species of theropod dinosaurs with downlike feathers on the body and tail. More spectacularly, the end of *Protoarchaeopteryx*'s tail sported a fan of feathers that are vaned, suggesting the presence of barbules. The second specimen, named *Caudipteryx*, had feathers attached to the second finger of its hands.

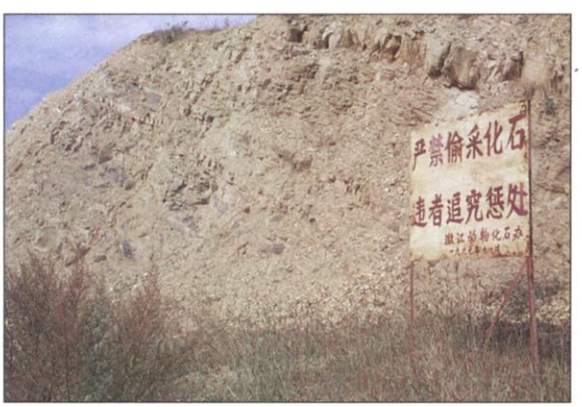
Unique window. Fossil beds in Liaoning give an unequaled view into Cretaceous life, like the bird *Confuciusornis* (right).

Skeptics of the bird-dinosaur link don't dispute the feathers, but they think *Caudipteryx* and *Protoarchaeopteryx* are flightless birds, not dinosaurs. The skeptics also pointed out that no feathers had been found in dromaeosaurs, the group of dinosaurs perhaps most similar to birds. Then in 1999, Wu Xiaochun, Xu Xing, and Wang Xiaolin of IVPP reported downy feathers on a 1-meter-long dromaeosaur named *Sinornithosaurus*. Last year, another dromaeosaur, named *Microraptor*, turned up with even more birdlike traits. "In terms of scientific significance for dinosaur evolution and the origin of birds, these fossils are as important as *Archaeopteryx*," says Chiappe. "It's the major breakthrough in this field."

Key mammals

Mammal paleontologists have made equally important discoveries in the Liaoning fossil beds, although the finds have tended to raise more questions than answers. The origin of mammals has always been a puzzle with most of the pieces missing, because these small animals fossilize poorly, if at all. All around the world, most Mesozoic animals are known solely from isolated fossils of teeth. As with dinosaurs and primitive birds, the extraordinary preservation at Liaoning has helped fill in the picture.

In 1999, the field got its first relatively complete specimen of a triconodont, an extinct group of mammals previously known only from teeth, jaws, and a few skull fragments. The 125-million-year-old creature, dubbed *Jeholodens*, was described by Ji Qiang, Luo Zhexi of the Carnegie Museum of Natural History in Pittsburgh, and Ji Shuan. It's believed to be close kin to the common ancestor of all living mammals—both the more primitive, egg-laying monotremes like the platypus, and the therians, the group that includes marsupials and placental mammals. "One of the holy grails of paleontology is to find the ancestor of living mammals," says Tim Rowe of the University of Texas, Austin. "*Jeholodens* is the closest thing."



Early days. The Chengjiang formation in Yunnan reveals the evolution of some of the first animals.

The "stunning" completeness of the specimen reveals an odd trait: *Jeholodens* held its forelimbs under its body, while its pelvis retained the sprawling posture of reptiles. The find could mean that the upright forelimbs evolved once, in this common ancestor, and were later lost in monotremes, which have sprawling limbs in addition to their other reptilian traits. Or it could be that the modern forelimbs evolved in triconodonts only after that group split away from the lineage that led to living mammals. The modern forelimbs would then have to evolve a second time (along with modern hindlimbs) in the therian mammals.

The action isn't just at mother lodes like Chengjiang or Liaoning, either. All across the country (see map, p. 234), Chinese and Western scientists are helping to solve paleontological problems. Take recent findings that shed light on the nature of the largest-ever mass extinction some 245 million years ago. "If you're interested in the Permian-Triassic extinction," says the Smithsonian's Erwin, "you have to go to China." That's because there are at least 50 good sections in south China alone—three times as many as in the rest of the world. Collaborative work between Erwin and a team led by Jin Yugan of NIGP has shown that the extinction was sudden, rather than drawn out. Isotopic changes measured by Erwin, Jin, and geochronologist Samuel Bowring of the Massachusetts Institute of Technology could mean that the extinctions took place in as few as 10,000 years (*Science*, 15 May 1998, p. 1007). A quick pace is consistent with a catastrophic cause of extinction, such as an asteroid impact, rather than a gradual change in sea level or climate.

All this activity generates a self-reinforcing cycle, says Currie, a longtime China hand. The more that is published, he explains, the greater the buzz. The buzz leads to more collaborations, which result in more publications that attract more funding. "I don't see that this trend is going to stop," he says.

Indeed, the greatest threat to continued scientific productivity is an external one. At Liaoning and elsewhere, undiscovered fossils are threatened by looting and escalating prices on the black market (see p. 239). Although such activity could in theory exhaust this nonrenewable resource, both Western and Chinese paleontologists are optimistic that the new golden age will not lose its luster anytime soon. "There are many more important discoveries to be made," says Sun Ge of NIGP. What's been found, he says, "is just the beginning." **–ERIK STOKSTAD**

With reporting by Dennis Normile and Xiong Lei.

CREDITS: (TOP TO BOTTOM) D. NORMILE; IVPP; L. CHIAPPE