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The very old meets the very new as palaeontologists turn to cutting-edge technology to help unearth the mysteries of the past. **Crispin Andrews** reports.

GETTING DOWN TO THE BARE BONES

NO ONE KNEW the fossilised archaeopteryx that arrived at Stanford University in December 2009 would turn out to be one of the most significant palaeontological finds ever.

When the first of these 150-million-year-old dino-birds was pulled out of the ground in Solnhofen, Bavaria, in 1861, Germany was still a collection of autonomous kingdoms and principalities.

Ever since that first fossil find, experts have thought archaeopteryx the missing link between dinosaurs and birds. But, until now, no one knew for sure.

Stanford's archaeopteryx had been analysed before. To the naked eye, the magpie-sized fossil contained nothing more than rock and bone. Stanford scientists, however, had something a bit more powerful than the naked eye at their disposal. The University's synchrotron radiation lightsource, bright X-ray beam.

A closer look

Early palaeontologists relied on their digging tools and good eyesight. They made deductions about prehistoric creatures based on a superficial knowledge of the animal's anatomy and physiology. When, in 1822, Gideon Mantel famously found iguanodon bones in Tilgate Forest, Sussex, he thought he'd discovered a horned rhino-like reptile. By the time more complete iguanodon specimens showed that this Cretaceous giant was a biped with a large thumb claw, Sir Robert Owen had already installed models based on Mantel's original designs in the gardens of Crystal Palace.

Victorian scientists also believed that gastornis, a two-million-year-old predatory flightless bird, had a long-slender crane like neck – which as it turned out would have been too weak to support the animal's huge head and snapping beak. Others insisted that the giant sauropod brachiosaurus spent

Detailed synchrotron analysis has proved the archaeopteryx had both avian and reptilian features

most of its time underwater, and that elasmosaurus's long neck was in fact the marine reptile's tail. Further back, Ancient Greeks thought mastodon skulls, with their single central trunk socket, belonged to dead Cyclops.

Palaeontologists made the most of what they knew. Living lizards ran on all fours, with their belly close to the ground; ostriches and emus, the largest living flightless birds, had long necks. Something long and whip-like with lots of vertebrae usually meant a tail, and surely only an amphibious animal would have a nostril near the top of its head.

Interdisciplinary investigations

Today's fossil analysis is no longer the sole reserve of the palaeontologist. Technology has made it an interdisciplinary science – one that needs specialists. The Stanford group included a geochemist, physicists, geologists and a computational zoologist. Using cutting-edge technology, these, and other scientists like them, are uncovering some of the prehistoric world's best kept secrets. And according to Dr Phil Manning of Manchester University, who led the project, there's more to come.

"It [palaeontology] used to be like throwing a few dead chickens and a bag of gravel into a washing machine to see what happens," says Dr Manning. "Now we have the potential to map organic molecules within a fossil and to understand the kinetics of what happens when something is preserved in the ground for 65 million years."

Located at the US Department of Energy's Stanford Linear Accelerator Laboratory, the synchrotron is a particle accelerator that revs electrons to nearly the speed of light. Its bright X-ray beam is 100 million times brighter than the Sun's rays, and is used primarily for advanced energy-related research in materials science biology. The Stanford team used it to create a 100-micron pinhole X-ray beam that could map elemental composition at any spot on the fossil.

"The smaller the pinhole the better resolution and the finer the detail, but fewer X-rays hit the specimen's surface," says Roy Wogelius, an inorganic chemist from Manchester University and part of the Stanford team.

Chemical connections

Archaeopteryx had feathered wings, scales and teeth. That much has always been known. It looked like a link between dinosaurs and birds. But until the Stanford synchrotron team got their hands on this particular specimen, no one had demonstrated a solid chemical connection.

Scientists had already determined the presence of minerals in prehistoric fossils, but the Stanford team were the first to analyse a fossil in situ. Using the synchrotron, the team discovered that the fossilised archaeopteryx's feathers contained phosphorous and sulphur, elements found in modern bird feathers. They also found copper and zinc traces in the dino-bird's bones. These chemicals were present in the original animal and had not leached into the fossil from the surrounding rock during the last 150 million years.

"The synchrotron maps where the copper is and also the elements that surround it," says Wogelius. He explains that if the copper is surrounded by sulphur, it's likely to be inorganic – leached into the specimen from its environment. Surrounded by oxygen or nitrogen, it's more likely to be organic, from the animal. "Looking at the fossil in context you can make a good statement that the copper and zinc was from the original bone," Wogelius explains. He also says that the archaeopteryx definitely had reptilian and avian features.

Dr Manning's team used the synchrotron again last year on a fossilised confuciusornis sanctus, the earliest known bird with a toothless beak. Originally discovered in China and named after the country's great moral philosopher, Dr Manning and his team used the copper map inside the fossil to work out the 120-million-year-old dino-bird's pigmentation.

"By mapping the copper we were able to also map the distribution of pigment within the organism," says Wogelius. Copper, he explains, is a biomarker for the eumelanin pigment, the pigment that gives dark shading to human hair, reptile skin, and bird feathers. "We haven't worked out how to detect other pigments yet," he adds. "We have a black and white picture of what confuciusornis sanctus looked like."

The team also uncovered more evidence as to the organic nature of the copper inside the fossil. "The synchrotron also maps distance between the copper and the surrounding elements," Wogelius says. "We found that the distance between copper and oxygen deposits was identical to that in the eumelanin found in living organisms."

Dr Manning says they are still a long way from discovering prehistoric animals' colour, but believes that pigmentation could be even more important determinant of behaviour. "Pigmentation is a crucial interface between an organism and its environment," Dr Manning says. Think of a flamingo with its pink shrimp diet, or the black wolf whose colour gives it a predatory advantage in heavily forested areas. "Pigmentation means adaptation, and if we can map the presence of this in an extinct organism, we can start asking questions >

< about when the adaptation first happened and why."

Fleshing out knowledge

In 1997, palaeontologists dug something remarkable out of the North Dakota desert. An 8m-long mummified dinosaur covered in skin.

Not long ago, getting this hadrosaur out of the rock without destroying the fragile skin would have been impossible. The North Dakota scientists, however, didn't need to get out their chisels. They used the world's largest computerized CT scanner, originally built by NASA to scan space shuttle parts for flaws, to work out exactly where the bones were.

Soft parts of dead animals normally decompose rapidly. Because of chemical conditions where this dinosaur died, fossilisation – replacement of tissues by minerals – took place faster than decomposition, leaving mineralised portions of the tissue intact. The Dakota hadrosaur was preserved by a hard iron carbonite called siderite. The siderite also preserved tendons, ligaments and, according to researchers, maybe some internal organs. "The CT scans enabled us to see through the iron carbonite and the plaster casting to map the specimen," says palaeontologist John Hoganson from North Dakota State University.

Medical CT scanners spin around the patient. With the Boeing scanner, the specimen spins around inside the machine. At 8,000lb, the hadrosaur was the largest object it has ever scanned at high resolution. The bulk of the specimen required nonstop scanning, 24-hours a day, for three weeks. "Over six months, the hadrosaur logged around 500 hours under the scanner," Hoganson says.

So far, scientists have calculated that this dinosaur had 25 per cent more muscle mass in its hindquarters than previously believed. They now believe that these herbivores could run up to speeds of 45km/h, easily outpacing T-Rex and other large Cretaceous predators.

The hadrosaur is bigger than they thought, too. A 1cm gap between each mummified vertebra added an extra metre to previous predictions. This hadrosaur was actually 12m long. They also found evidence that it may have been striped.

Cat scans

Besides T-Rex, there is no more intriguing prehistoric creature than smilodon – the infamous sabre-tooth cat. With its giant canines, it looked as efficient and deadly a killer as the prehistoric world had ever evolved. Smilodon, it was always believed, would leap on a prey animal's back, cling on with its sabres, and then use them to inflict the killer blow. When Colin McHenry from the University of Newcastle, Australia, looked more closely, smilodon's physiology told a different story.

"From a biomechanical point of view this sort of hunting technique wouldn't have been a good behaviour," he says. "The smilodon's skull wasn't strong enough to cope with the forces; it would be running a high risk of a fracture."

Predators tend not to take risks. Just a broken tooth would leave hunting or defending its territory difficult for the cat.

McHenry created a 3D sabre-tooth skull using a computer programme called Mimics. The programme stacked hundreds of 2D CT scans from the original skull on top of one another to create an image that gave him the shape and bone density. It didn't tell him how the skull moved, but McHenry had another technology up his sleeve. Finite element analysis.

Engineers use this technology

CT SCANS

MORE THAN SKIN DEEP

With today's technology, scientists don't have to unwrap a mummy to discover its secrets. Last year, staff at Scotland's National Museum conducted a non-invasive analysis of a 2,000-year-old mummy. The specimen, part of the museum's Fascinating Mummies Exhibition, gave them fascinating insights into Ancient Egyptian life.

"Medical CT scans enabled us to see inside the wrappings, without damaging the body inside," says Dr Jim Tate, the museum's head of conservation and analytical research. "With specialists in a range of fields we then analysed the data in detail."

At first glance, the Rhind Mummy didn't give much away. Named after Scottish explorer Alexander Henry Rhind, who excavated it from Thebes in 1857, museum scientists didn't know anything about the person inside the wrapping – not their age, their sex nor their status.

Tate's team used CT scans to produce a digital image of the skeleton. From the pelvis shape and cranial metrics, University of Edinburgh forensic pathologist Dr Elena Kranioti identified a young woman – aged between 25 and 29 when she died. Kranioti could estimate age as the woman's skeletal elements were fused but there was no sign of arthritis or bone spurs. Healthy teeth suggested a good diet.

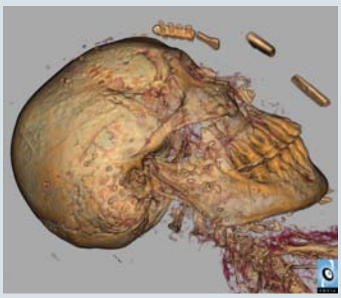
"We couldn't find a cause of death," says Kranioti. "There was no obvious pathology and only a post-mortem fracture near the nose where the brain was extracted during the mummification process." Kranioti believes the woman died quickly, perhaps from an infection. "She wasn't royalty, but was well preserved, probably a rich family's servant."

Medical CT scanning produced detailed 3D images of the Rhind mummy

Scans also uncovered a scroll, inside the mummy's wrappings, in the woman's hand. It's thought to contain instructions for her embalming and afterlife. Two other mummies excavated from the same tomb in 1857 also held this so-called Book of Breathing. It probably contains the Rhind mummy's name to ensure her eternal life, as was the ancient Egyptian custom.

Underneath the wrappings, the Rhind mummy was wearing a gold foil amulet. Edinburgh University's Clinical Imaging Research Centre used scan data to form a 3D image and 3D CAD data and, with this, engineers at the University of Liverpool produced a titanium replica using a process called Selective Laser Melting.

Joseph Robinson explains that a high-powered laser beam created three-dimensional metal parts from 50μm thick 2D layers of the 3D CAD file.



Skull scan revealing a post-mortem fracture made during mummification

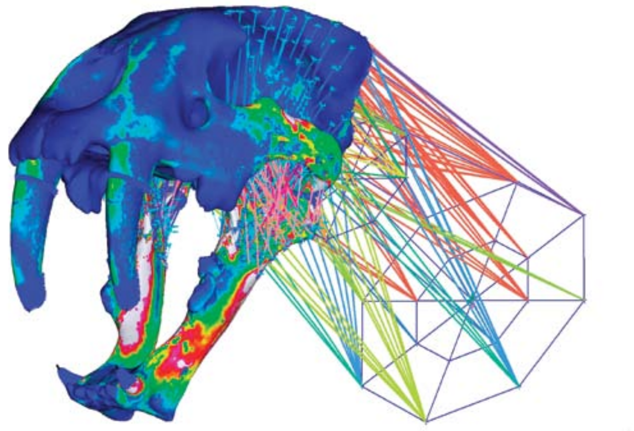
"You slice the CAD data into layers and use a 200W laser to fuse the fine metallic powder, which has been evenly distributed across a substrate plate, together," he says.

This process takes place inside a chamber containing a tightly controlled atmosphere of inert gas, either argon or nitrogen, at oxygen levels below 500 parts per million. The laser energy is intense enough to melt the particles into solid metal. The Liverpool team repeated the process, layer after layer, until the part was completed.

Tate wants to see the Rhind mummy's scroll and discover her name. A high-resolution CT scanner, big enough to fit a person inside, could provide data that might virtually un-roll it. "Unfortunately, most modern day scanners high-res enough to do the job only take objects the size of a baked bean tin," he says.

Tate adds: "This technology enables valuable cultural and historical specimens to remain intact, waiting for further scientific advances that can tell us even more."

The Fascinating Mummies exhibition looks at death and afterlife rituals and the history of Egyptian research in the last two centuries. Running until 27 May, it includes painted coffins, amulets, jewellery, papyri, embalming equipment and ornaments dating back 6,000 years.



Researchers at the University of Newcastle, Australia, have used 3D modelling techniques to paint a clearer picture of the smilodon's hunting techniques

to evaluate structural stresses on aeroplanes and bridges. "On complex organic constructs, like the skull of a prehistoric cat, the engineering equations don't work," McHenry says. His computerised sabre-tooth skull gave him another option, though. He broke down the irregular skull shape into two million tiny squares, or elements. The technology could then analyse these regular shapes with an engineering equation. "It was like making a 10ft-high Lego skull," McHenry says. "Think of it like digital crash-testing."

McHenry ended up with a colour-coded map showing the stress biting, shaking, twisting and raking back on prey would inflict on the sabre-tooth's skull. A computerised lion's skull coped well with such forces, but "the smilodon's lit up like a Christmas tree", McHenry says. "Lions have smaller, stronger conical shaped teeth and could let the prey go more quickly."

McHenry also discovered that the sabre-tooth's jaws could apply only about 220lb (100kg) of pressure – a third of the bite strength of a lion. A 230kg smilodon, he argues, would have a bite force of about 1,000 Newtons from its 20cm-long canines: about the same as an 80kg jaguar.

"Smilodon was a strong, robust animal with large muscles on the underside of its neck, capable of wrestling large prey to the ground," McHenry says. "Those famous sabres would most likely be used to finish off the prey with a precise bite, probably to the neck."

Fossils and forensics

McHenry used the same technology on a kronosaurus skull, discovering that the huge marine pliosaur was more suited to tackling smaller prey.

From similar experiments, Dr Manning deduced that velociraptor's famous sickle-like claw was too weak to deliver a killer blow, and was more likely used to help the dinosaur climb trees, or to hold prey down while razor sharp teeth finished them off. "Just because it [the claw] looks dangerous, doesn't mean it is," Dr Manning says. Tests showed that even at full running speed, velociraptor's claw could hardly puncture the skin. To shred and disembowel it would have needed a metal claw.

Technology has turned palaeontologists from fossil hunters into crime scene investigators. They undertake intricate chemical and biomechanical analysis to come up with fascinating insights into the prehistoric past. Without all the facts, they're still at the stage of eliminating the impossible or putting forward the most likely solution, but as the technology improves so too will their certainty and accuracy.

The Dakota hadrosaur is still under investigation and only a fraction of its secrets have been revealed. Later this year, the Stanford team will announce "further synchrotron findings of a significant nature". Dr Manning, who calls himself a geo-biologist, is looking forward to getting his hands on fossils that have sat in museums for years, their analysis apparently complete.

"For years it has been like trying to read a book from just a few lines," Dr Manning says. "Now, at least, we've got a few pages." *