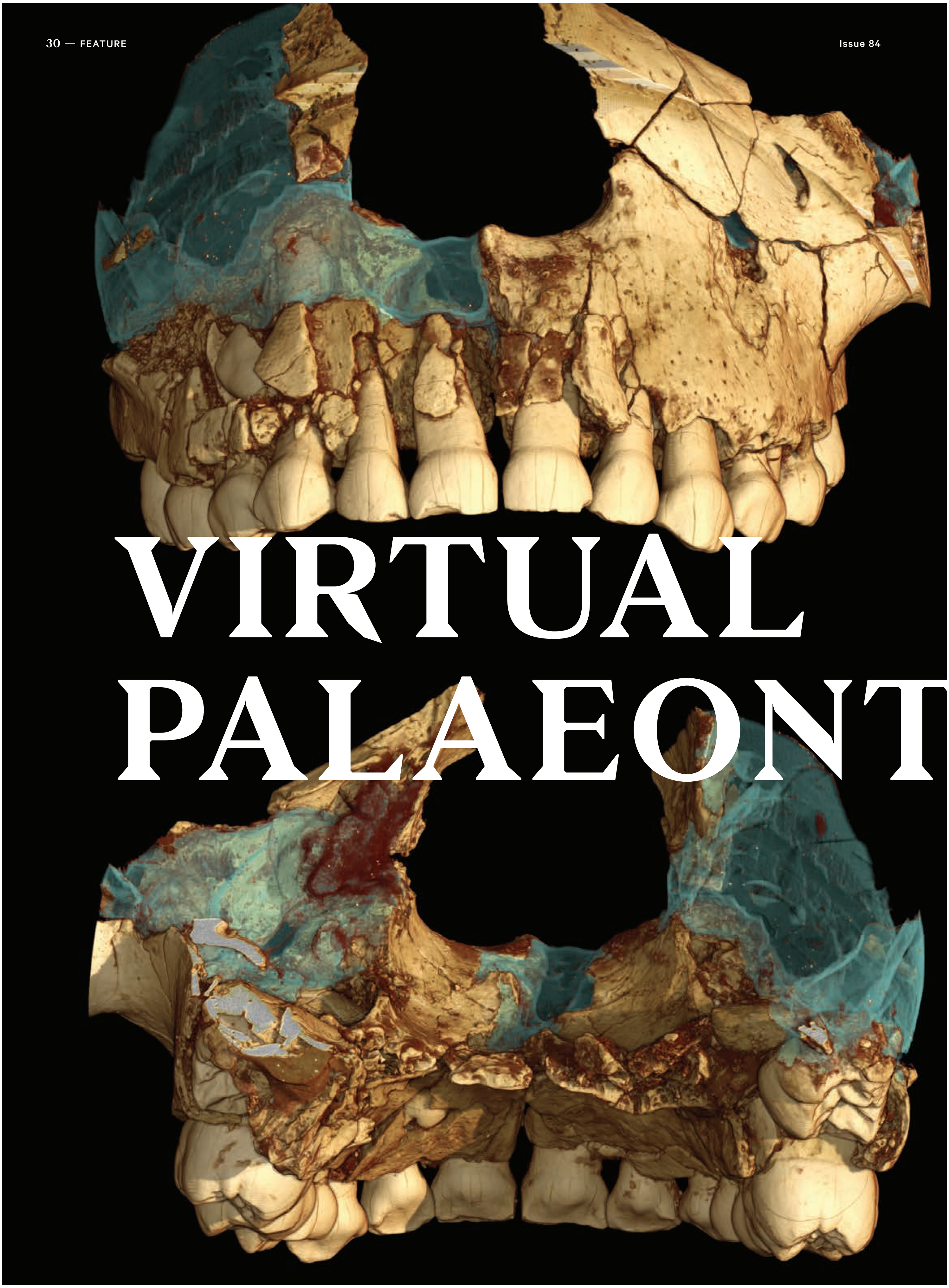
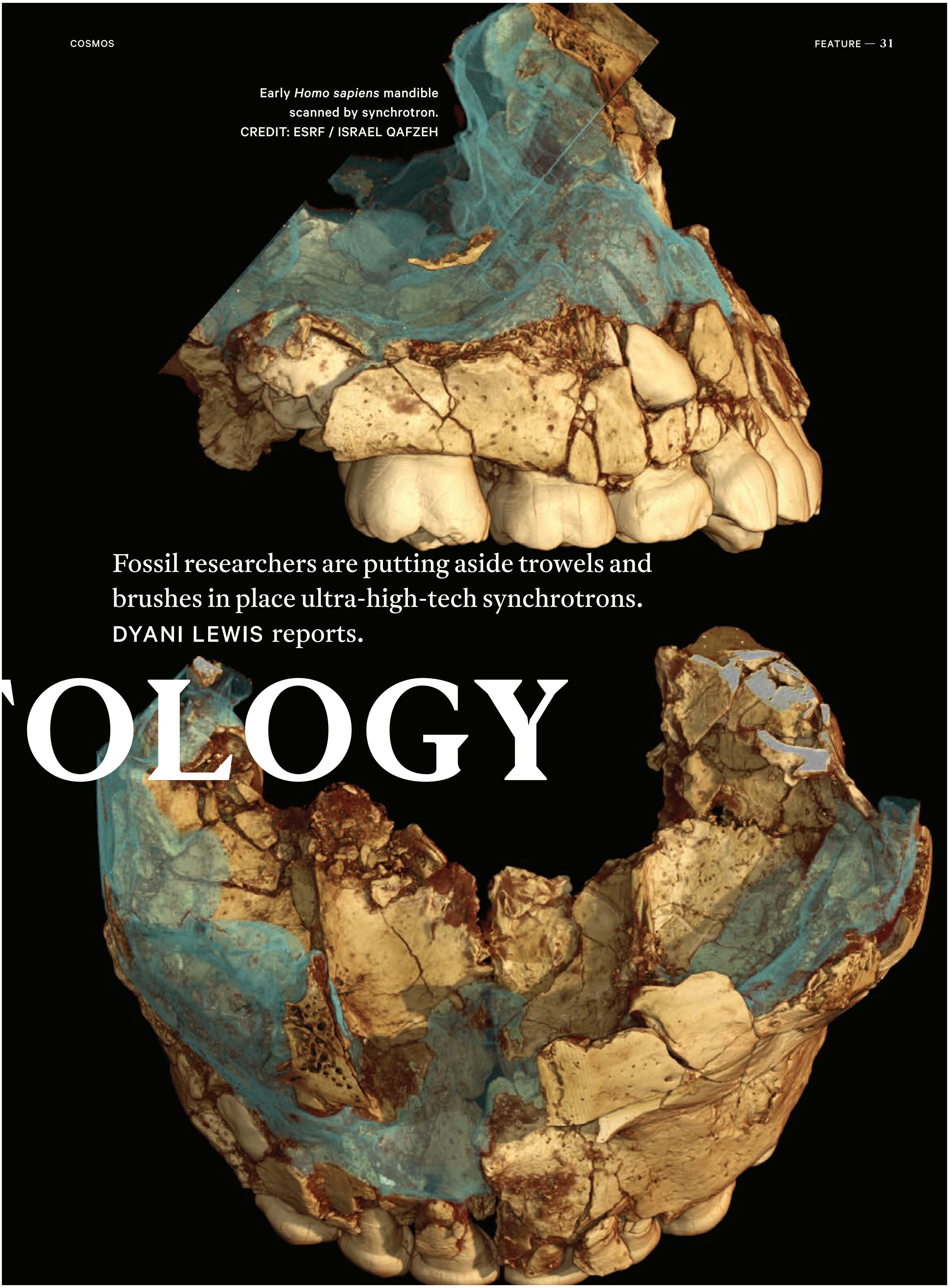


VIRTUAL PALAEONT



Early *Homo sapiens* mandible scanned by synchrotron.
CREDIT: ESRF / ISRAEL QAFZEH

Fossil researchers are putting aside trowels and brushes in place ultra-high-tech synchrotrons. DYANI LEWIS reports.

OLOGY

AS FAR ANYONE CAN TELL, the briefcase sized slab of sandstone was surreptitiously cut from the Gobi Desert in southern Mongolia sometime prior to 2011.

BY 2015, it had been spirited out of the Central Asian nation, passing through the hands of private collectors in China, Japan, the UK and elsewhere, and into the possession of Fran ois Escuilli , a French palaeontologist and fossil dealer.

It wasnít, of course, the sandstone that Escuilli was interested in, but the near complete skeleton of a duck sized dinosaur it encased. The fossil that lay half buried, half exposed in the red rock was clearly a striking specimen.

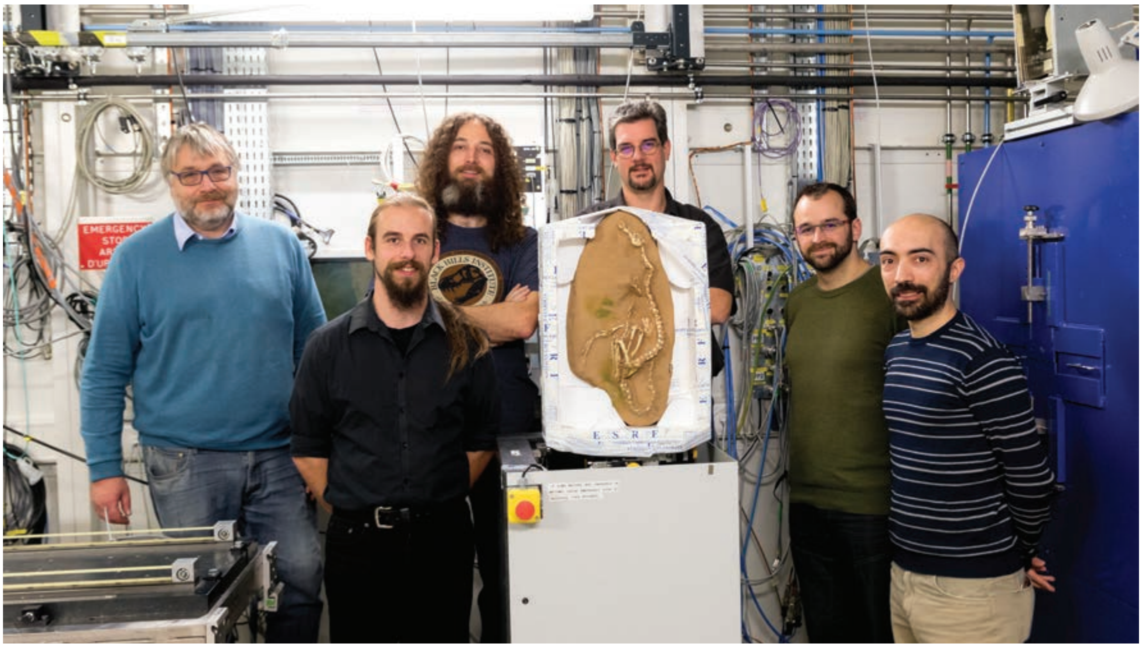
Escuilli knew he had an important find on his hands. But instead of offering it up to the highest bidder, he handed the poached dinosaur to Andrea Cau and colleagues at The Royal Belgian Institute of Natural Sciences in Brussels, who would work out what it was, and then return it to Mongolia.

When Cau first set about identifying the long dead animal, he was dubious. Palaeontologists have been chipping away at Mongoliaís fossil rich Djadochta Formation for decades. That single ancient layer of Cretaceous rock has given the world some 5% of all known dinosaur species.

Among its most treasured finds is *Velociraptor* of *Jurassic Park* fame, along with numerous other members of the dinosaur family that gave rise to modern birds. But the dinosaur hotspot formed some 71 75 million years ago has become a magnet for unscrupulous fossil poachers.

The fossil was unlike anything Cau had seen: a bizarre mix of features that donít usually belong together. Along with the shady history of how it left Mongolia, there were other ominous signs: bits of bone knocked loose by the poachers had been glued back into place and plaster filled out parts of the skull.

Cau, now at the Giovanni Capellini geological and palaeontological Museum in Bologna, Italy, wasnít sure whether what he was looking at was fabulous or fraudulent. We wanted to be sure that it was not a chimeraí assembled using bones from different dinosaurs or even including fake bones, he says.



The team of scientists at the European Synchrotron Radiation Facility in Grenoble, France, ready to scan the *Halszkaraptor escuilliei* fossil. From left to right: Pascal Godefroit, Vincent Beyrand, Dennis Voeten, Paul Tafforeau, Vincent Fernandez, Andrea Cau.

CREDIT: ESRF / P JAYET

The Synchrotron allowed a 3D render of *Halszkaraptor escuilliei* to explore, leading to a greater understanding of its structure and habits while keeping the fossil undamaged.

CREDIT: ROYAL BELGIAN INSTITUTE OF NATURAL SCIENCES; SAINT THOMAS PRODUCTION

Itís a legitimate concern: in 1999, *National Geographic* magazine unveiled the birdlike Archaeoraptor, a claimed missing link in dinosaur evolution. The fossil was later revealed to be a clever forgery, a glued together mash up of spare parts from at least two different species.

Cau wasnít taking any chances. He flew the fossil to Grenoble, at the foot of the French Alps. There, he blasted the slab of sandstone with X rays so powerful they penetrated the rock to reveal the skeleton locked inside, down to its tiniest detail.

The results removed all doubts: the fossil, which Cauís team named *Halszkaraptor escuilliei* (honouring Escuilli for the specimenís return), was no fake. But thatís not all the particle accelerator at the European Synchrotron Radiation Facility (ESRF) did.

With the six terabytes worth of data collected, Cau and his colleagues created a virtual fossil a digital facsimile they could turn over and inspect on a computer screen.

The slender swan like neck, the duck billed head, the flipper shaped forelimbs, and the fierce hind claws were all thrown into sharp relief. They had uncovered a strange dinosaur, an earthbound predator that swam and hunted fish in the late Cretaceous wetlands.

The powerful X ray beam revealed an even deeper truth than simply what *Halszkaraptor* looked like. Peering inside the bones, Cauís team could see individual growth rings similar to a treeís growth rings that showed the creature to be around two years old when it died.

Exposing this level of detail without painstakingly excavating each and every bone from the rock, and without slicing priceless fossils in half, was unthinkable just 20 years ago. Palaeontology still conjures up images of intrepid fossil hunters prizing apart shale with a pick axe or sifting through dirt on a cave floor. But thatís changing.

Scientists like Cau are turning to virtual fossils, warding off the kind of damage that leaves caliper marks on irreplaceable pieces of the Earthís natural heritage, and laying bare intricate details that give scientists insights into prehistoric life like never before.

PALAEONTOLOGISTS FIRST SEIZED on flesh and bone penetrating X rays not long after Wilhelm R ntgen snapped the first X ray image, of his wifeís hand, on a December day in 1895. After the discovery of the mysterious Piltdown Man remains in 1912 a proposed missing link between apes and humans it was X ray images of the jawbone and teeth that British scientists turned to, to check their authenticity. The remains were later shown to be a forgery.

In the 1970s, palaeontologists were again taking note when hospitals began installing medical computed tomography (CT) scanners: machines that combined X ray measurements from multiple angles into virtual slices through an entire specimen.

By the mid 1980s, pioneers in the field, such as palaeoanthropologist Glenn Conroy from Washington University Medical School in St. Louis, Missouri, were taking CT scans of some of humanityís earliest known relatives, peering into skulls filled with stone to see how brains swelled with the march of evolution.

Synchrotron particle accelerators like the one in Grenoble turbo charge X ray technology further still. While Conroy was looking at medical CT scan slices about as thick as a coin (two millimetres), synchrotrons slice fossils into slivers just 1/1000th of a millimetre thick. The resolution today is at least a four fold improvement on the best CT scanners.

But itís not just about resolution. Synchrotrons see things that are invisible to conventional medical CT or even the highest resolution micro CT scanner. In a CT scanner, dense materials show up because they stop more X rays from passing through. But a synchrotron also picks up the tiny deflections that occur when X rays pass from one material to another, even if they have a similar density. The outline of a fossil embedded in rock, for instance, or an insect trapped in amber, pops out, clear as day.

The making of the synchrotron as the high tech go to tool for palaeontologists is largely down to the dogged work of Paul Tafforeau. In 2000 he was completing his PhD, looking for ways of viewing the insides of fossil teeth without cutting into them. Micro CT was new at the time, but even that wasnít up to the task. A chance conversation with Jos Baruchel, then head of the imaging group at the synchrotron, set him on a new path.

On weekends and during holidays whenever Baruchel found a free slot in the busy schedule Tafforeau would pack his extinct primate teeth into his bag and make the four hour drive from Montpellier to Grenoble. The synchrotron exposed exquisite details of the internal microstructures of teeth, features that were previously only seen by slicing a tooth open, destroying it in the process.

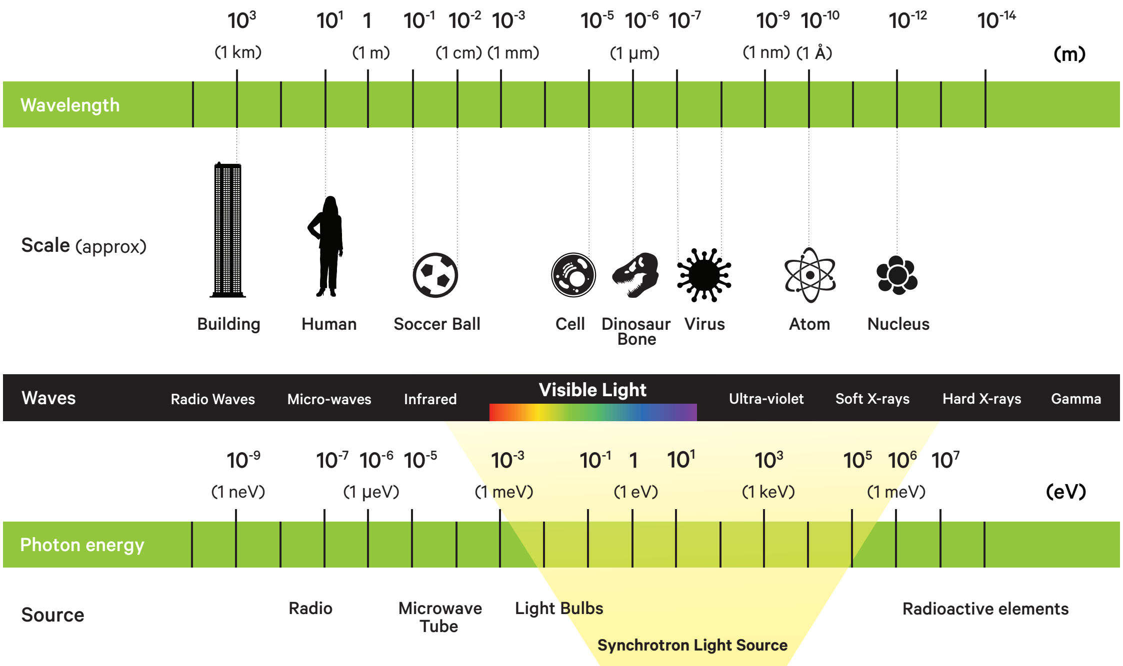
For fossil material, itís becoming the gold standard, says palaeoanthropologist Tanya Smith from Australiaís Griffith University, who has been working with Tafforeau on the teeth of Neanderthals and other prehistoric human relatives since 2004.

By that time, Tafforeau had finished his PhD and chalked up enough wins that the ESRF decided to bring him on as a palaeontology imaging specialist. Itís still the only synchrotron in the world to employ a dedicated palaeontologist.

TEETH ARE OFTEN THE LAST remaining vestiges of our past. When bones disintegrate, teeth endure. A single tooth can rewrite what we know about when and where our ancient relatives lived. But a single disembodied tooth can also confound, because itís not always clear who the tooth belonged to.

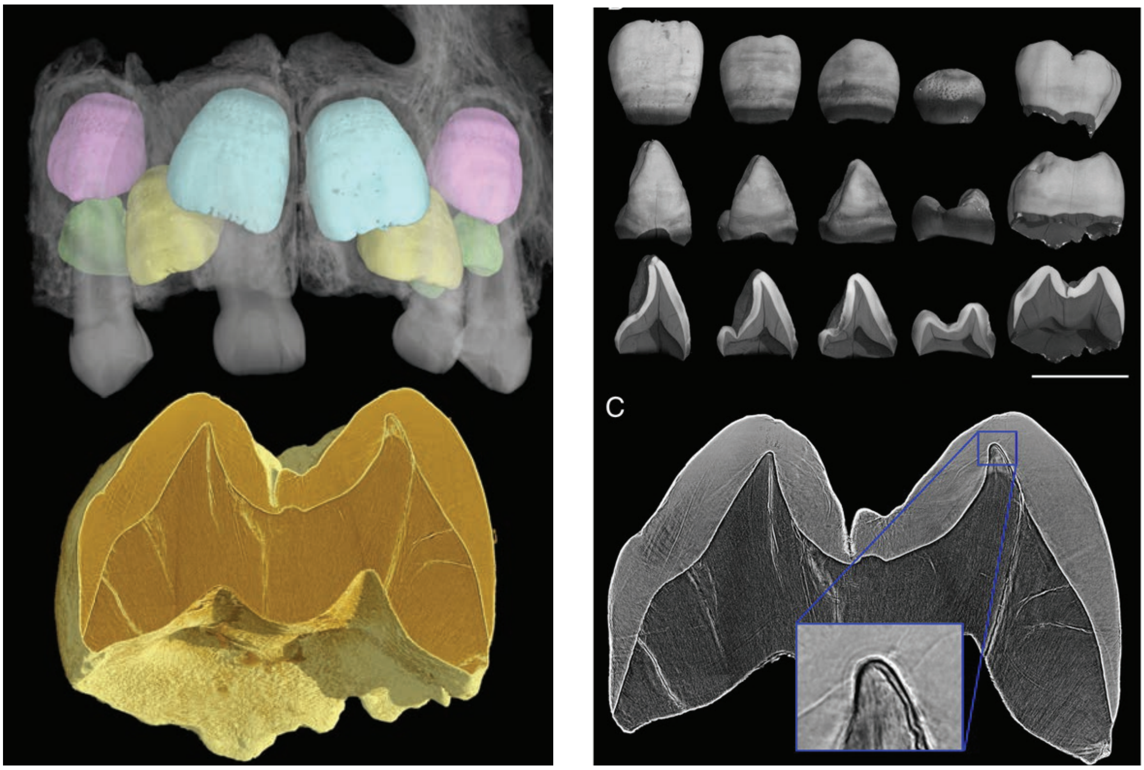
From the outside, you canít tell: is it an orangutan or a human? says Smith. That changes when you can glimpse whatís inside. The thickness of the enamel and the shape of the underlying dentine can give crucial clues.

In 2009, Smith and Tafforeau put to rest a debate that had simmered for more than a century. When



Synchrotrons produce high-energy X-rays, generally with wavelengths in the 0.10–0.01 nm range, or energies in the 10–120 keV range. The high energy X-rays penetrate deeper into matter than X-rays with energies below 10 keV. An upgrade at the ESRF will allow larger specimens and Egyptian mummies to be scanned using this cuttung edge technology.

ILLUSTRATION: SHAWNEE WILLIS



A synchrotron scan (above, left) of a Neanderthal child's maxilla highlights the permanent teeth: central incisors in light blue, lateral incisors in yellow, canines in pink and third premolars in green. The deciduous ('baby') teeth are grey. Cross-section slices, top right, show the extent of enamel development. The neonatal line revealed in a first molar's dentine tip, bottom right, suggests that the tooth part began forming about 17 days before the child's birth.

CREDIT: PNAS

Eug ne Dubois uncovered teeth, a thigh bone and a chunk of skull during excavations on the Indonesian island of Java in the 1890s, he thought heíd found the coveted missing link between apes and humans. Unlike the forged Piltdown Man, the specimens were genuine.

But not everyone was convinced by the newly described Java Man . Some thought them ape; others, modern humans. Images captured by the synchrotron settled the debate once and for all. Digital sections of the teeth revealed internal structures that confirmed the Java Man molars were from *Homo erectus*, an archaic human lineage not ape, nor modern human that arrived in Indonesia as far back as a million years ago.

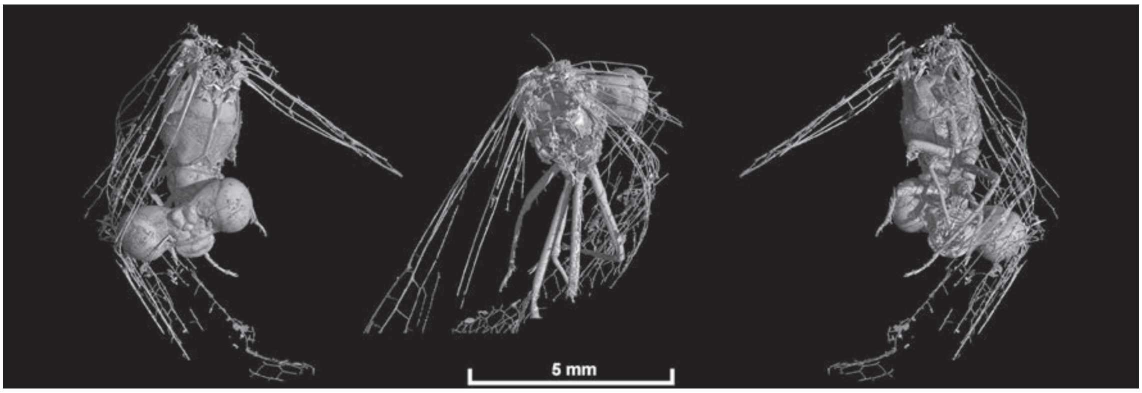
Virtual teeth are also writing, for the first time, the history of how modern childhood evolved. Compared to our closest living relatives, humans have a protracted childhood. We are utterly dependent on our parents until at least the age of six or seven, and continue developing through a teenage phase, the only animals to do so. Our cousins, chimpanzees, fend for themselves far earlier and reach adulthood in half the time.

What Smith and others wanted to know was how far back in the human family tree this lengthy childhood could be traced. That data is locked inside teeth. As teeth develop, they squeeze out enamel in a daily rhythm producing tiny internal growth lines similar to tree rings, and the *Halszkaraptor*ís bones in the enamel. Longer period lines and stressful events like birth are etched onto the outside of the tooth. Together, these marks can be used to calculate how long a tooth takes to grow and erupt.

For five years, Smith and Tafforeau got hold of as many teeth as they could from the Middle Palaeolithic, between 30,000 and 200,000 years ago. Museum curators came around to the idea that they could safely put their priceless specimens in front of Tafforeauís 60 kilo electron volt beamline one of 47 at the facility.

A person would be dead inside an hour, but a fossil tooth or a jaw with unerupted teeth still embedded within the bone would be undamaged. Curators brought teeth from nine Neanderthals and three Palaeolithic *Homo sapiens* to the synchrotron samples unlikely to ever be cut. That type of project, where you look at a larger cohort of individuals, wasnít possible using physical [sectioning], says Smith. If you look at a single fossil, itís really hard to tease out, do they differ on average?

And the results: In all cases, [Neanderthal] teeth are growing faster, says Smith. Theyíre maturing more quickly than modern humans.



Synchrotron X-rays allowed researchers to identify differences in the vein structure of Cretaceous-period damselflies encased in Burmese amber, leading to two new species: *Burmahemiphlebia zhangi* and *Palaeodysagrion cretacicus*.

CREDIT: ESRF

Neanderthals werenít maturing as fast as chimpanzees, though. Neither were our more distant relatives, *Australopithecines* from Africa that lived one to two million years ago, suggesting that childhoods have been slowing in our branch of the family tree line for a long time, but the brakes have really been put on in our own species relatively recently.

TAFFOREAU HASN'T JUST BEEN lashing teeth with the synchrotronís X rays. While completing his PhD, he was already convincing others to test the machineís mettle with their own specimens.

Over the years, he and his colleagues have used the particle accelerator to lay bare intricate details of the only known example of a fossilised brain; the digested remains of fish and beetles encased in Triassic lungfish poo; and a benign tumour in the vertebra of a teenaged *Australopithecine* who lived in southern Africa nearly two million years ago, among others.

Some of the most spectacular discoveries made with synchrotrons are of animals in amber. Since ancient times, people have been turning fossilised tree sap which looks like honey turned to stone into jewellery and fineries. Gemstones with beetles or even small snakes and birds trapped inside are prized by private collectors and palaeontologists alike.

Not all amber is honey clear, though: opaque amber looks more like lumps of caramel toffee, and thereís no telling from the outside what lies within. But the X ray vision of the synchrotron sees straight through it.

You never know what you will find, says Tafforeau. We discover complete fossilised animals where we were not expecting them. Dozens of new ants, wasps and beetles from the Cretaceous have been discovered. One insect a dragonfly was named after Baruchel, the physicist who started Tafforeau on his synchrotron journey nearly two decades ago.

But the real challenge has been making scans of large objects possible. Almost as soon as he started full time work at the synchrotron, Tafforeau was asked to work out how to scan the near complete Touma skull, discovered in Chad in 2001. The seven million year old remains represent the oldest known hominin, the earliest human family member after the human and chimpanzee lineages split.

At roughly the size of a large eggplant, the Touma skull isnít huge. But itís large enough to absorb 99.99% of the X rays from the synchrotronís beam. Typically, an image can only be computed if at least 10% of the X rays pass through. Tafforeau was undeterred. I was not thinking like a physicist, he says, I was only thinking like a palaeontologist.

So, he tinkered. Fiddling with the beam parameters and the tomography algorithms he could fool the system into requiring fewer X rays to form an image. And a final trick: he placed the skull in an aluminium bowl to bounce more X rays onto the detector. After two years of troubleshooting, the Touma skull was finally scanned in 2006, blazing the path for even larger specimens, including, in 2016, Cauís sandstone entombed Halszkaraptor.

The synchrotron beam in Grenoble went dark in December last year for a 150 million Euro upgrade to a new Extremely Brilliant Source (EBS). On Tafforeauís beamline, the refurbished equipment is being designed with larger specimens in mind, ensuring that Grenoble will continue to be a mecca for palaeontologists.

When they re open the doors in early 2021, Tafforeau is hoping to scan some of the worldís most spectacular finds. He and colleagues have already done test runs of mummified animals in preparation for scans of complete Egyptian mummies in the larger beamline chamber.

Other curiosities are on his wishlist, too. Fossils as big as a 1.5 metre long skull of a Tyrannosaurus rex, for instance, could also be giving up their hidden secrets in coming years. Thatís completely impossible today with any synchrotron in the world.

DYANI LEWIS is a freelance science journalist based in Melbourne.