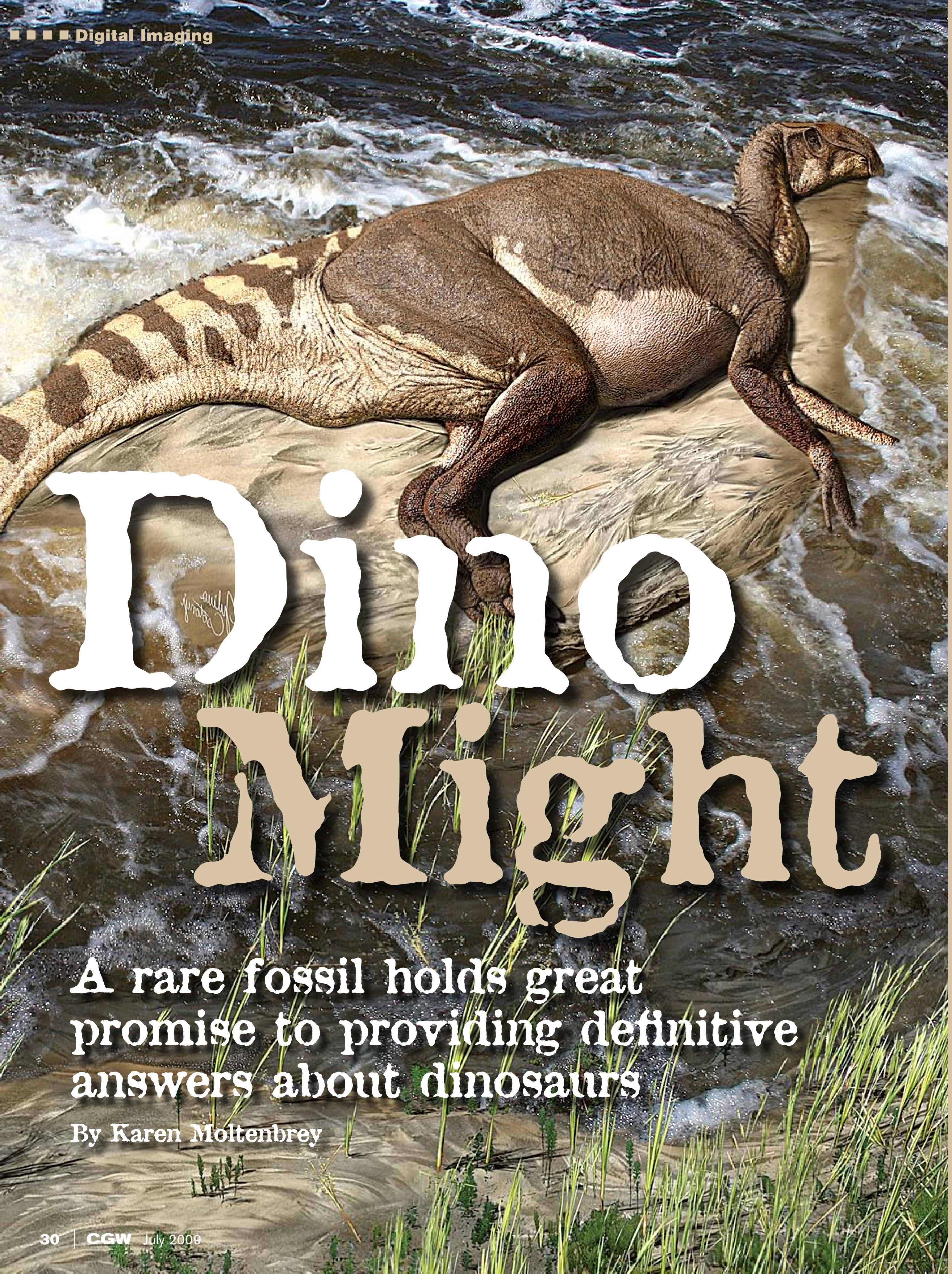
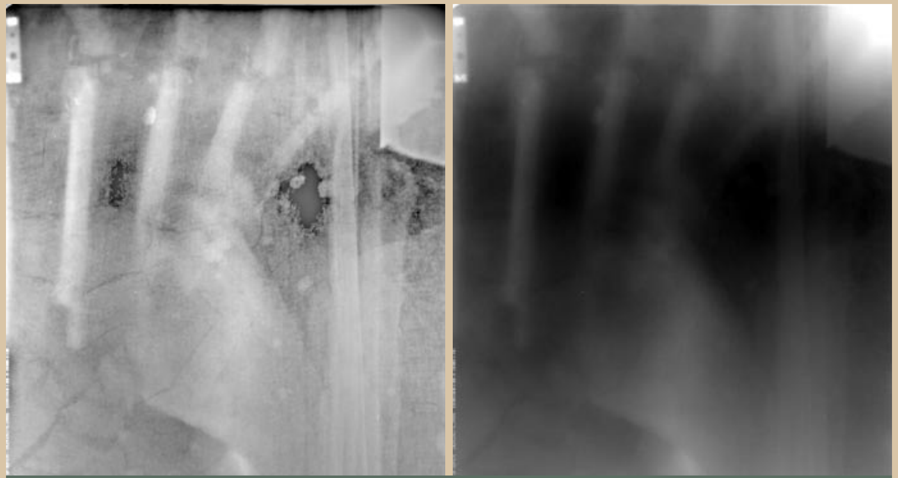


Dino Might

A rare fossil holds great promise to providing definitive answers about dinosaurs

By Karen Moltenbrey



Cutting-edge digital imaging techniques gave scientists a much clearer view of Leonardo's X-ray results. On the right is the original X-ray; on the left is the same image after further processing.

Leonardo was a *Brachylophosaur,* a short-crested lizard; a typical member of the *hadrosaurid* family. These duckbilled dinosaurs were common herbivores that roamed the earth more than 75 million years ago. Leonardo's life appears ordinary for his time. He lumbered through tropical forests, probably traveling in a herd. He ate vegetation—no doubt a lot of it. And he died suddenly and, it appears, violently, just as most of these beasts did. Today, though, Leonardo is considered quite extraordinary. He is one of the few articulated and partially mummified dinosaur skeletons ever discovered. And, he holds great potential in unlocking secrets to the late-Cretaceous past, finally giving scientists definitive information to so many questions that for years they could only answer speculatively.

Found in 2000 by fossil hunters near Malta, Montana, Leonardo (so named when the explorers found the moniker "Leonard" etched in a stone nearby) was quickly hailed as one of the most unique and important dinosaur finds in history. That's because most dinosaur discoveries consist of a crumbled piece of bone fragment; it is the culmination of many such fragments from various sites that compose the mounted fossils we see at museums (see "No Bones About It," February 2001). The fossil of Leonardo, on the other hand, was nearly intact, missing only part of the tail. Furthermore, he was articulated, meaning he retained his three-dimensional shape over many millennia. He is covered in fossilized skin, and his remains had been mummified by a natural event (see "Perfectly Preserved," pg. 36), leaving an excellent possibility that some of his internal organs and muscle are still present.

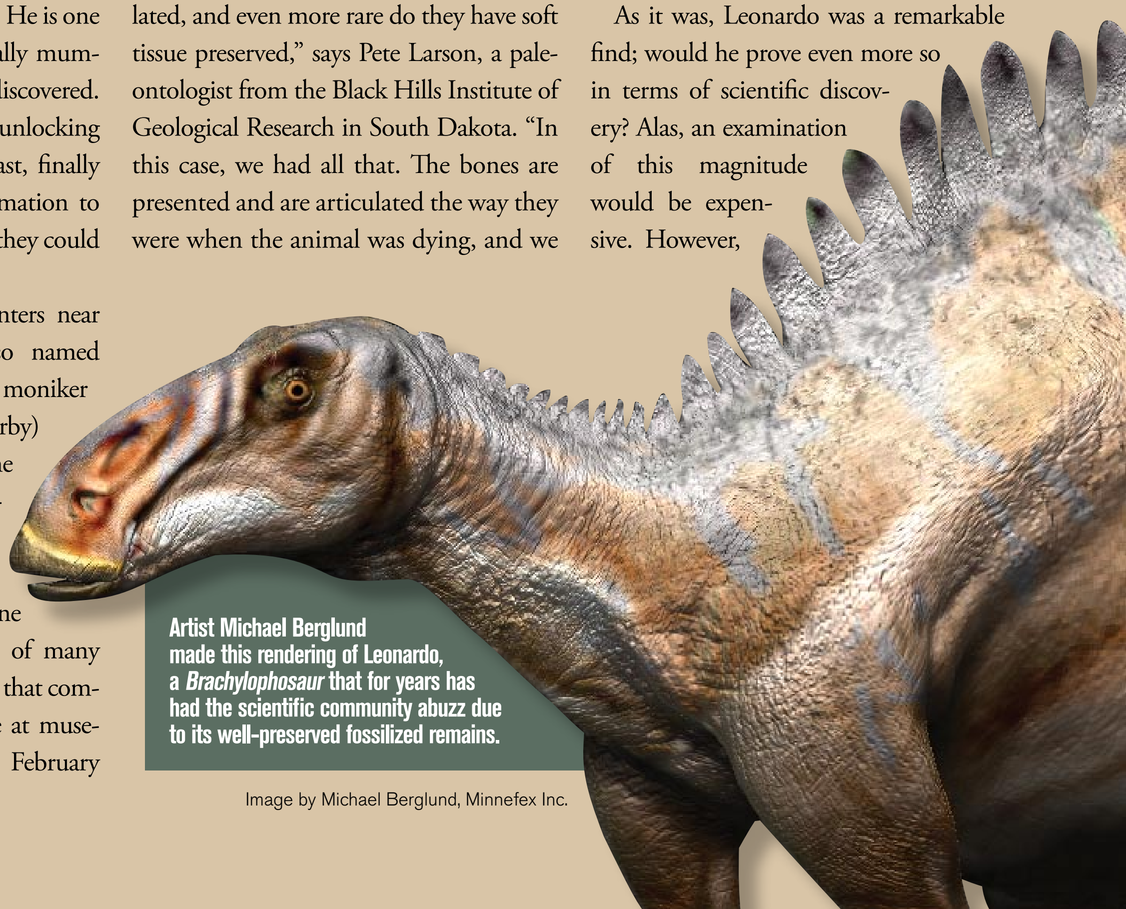
"Normally we just find bones, maybe skeletons. On rare occasion they are articulated, and even more rare do they have soft tissue preserved," says Pete Larson, a paleontologist from the Black Hills Institute of Geological Research in South Dakota. "In this case, we had all that. The bones are presented and are articulated the way they were when the animal was dying, and we had the preservation of the remains of soft tissue. So we can potentially study the digestive systems, respiratory systems, circulatory systems, and pulmonary-circulatory systems of these creatures. Potentially. We do not know yet if we will be able to do that, but it's specimens like this that offer us a chance."

Afterlife

In the summer of 2000, freelance paleontologist Nate Murphy uncovered Leonardo's mummified, fossilized body. Before the crew could transport the 6.5-ton block of dinosaur to a nearby vaulted studio, where Murphy and others would begin the meticulous cleaning process, a steel support structure was placed under the extremely fragile specimen to keep it from breaking apart.

Eventually, prominent scientists in the digital imaging fields were brought into the fold. Using cutting-edge techniques, they were able to conduct a virtual autopsy of sorts on the dinosaur, thoroughly examining him, both inside and outside, for clues as to how the prehistoric beast lived and died.

As it was, Leonardo was a remarkable find; would he prove even more so in terms of scientific discovery? Alas, an examination of this magnitude would be expensive. However,



Artist Michael Berglund made this rendering of Leonardo, a *Brachylophosaur* that for years has had the scientific community abuzz due to its well-preserved fossilized remains.

Image by Michael Berglund, Minnefex Inc.

© Black Hills Institute of Geological Research.

A white-light scanner (above) was used to generate an accurate 3D surface model of the dinosaur. (Inset) A close-up look at the beast's head and neck.

with such an opportunity looming, scientists and imaging specialists volunteered their time and loaned their expertise, while companies, such as Ford Motor Co., NDT Group, and Carestream Health, donated knowledge and expensive materials—all in the name of science. Some funding resulted when a film crew, led by Michael Jorgensen, documented a good portion of the project for the MidCanada Entertainment/Myth Merchant Films movie titled *Secrets of the Dinosaur Mummy*. Further work was advanced through the Judith River Dinosaur Foundation in Malta, which co-owns the fossil with the Hammond family, on whose land the specimen was found.

Art Andersen, president of Virtual Surfaces, was among those within the imaging community who became involved in the project. "I have done 3D scanning and editing for years, and I thought this would fit nicely into our work," he says. Andersen, whose experience spans industry as well as paleontology, was a catalyst for bringing many of the other scientists aboard.

The project was multifaceted. For a thorough look at the outside of Leonardo, the group would perform a digital scan, edit the resulting data into a single file, and later output a physical rapid-prototype (RP) model of the dinosaur. For an internal exam, the team X-rayed the specimen first on site at Malta and then at NASA Johnson Space Center's Ellington Field facility in Houston, later enhancing the data for a clearer picture. The crew also performed an elemental scan on a section of Leonardo, which analyzed the natural elements that were present in the body and offered clues as to the colors of his skin, for instance (see "It's Elemental," pg. 39).

Scratching the Surface

On the outside, Leonardo is well preserved, albeit extremely fragile. So when it came time to make a mold and cast of the dinosaur, the usual process of covering the surface in latex or silicon rubber was out of the question, as it was sure to permanently damage the once-in-a-millennia discovery. Furthermore, the chemicals from the process likely would have contaminated the fossilized skin, making it impossible to do certain types of testing.

"He has a lot of cracks and loose parts on him, and traditional modeling or casting could have destroyed him," says Andersen of the fossil. Moreover, Leonardo's frail state prohibited him from being transported to various labs for further examination. Alternatively, the group decided to employ white-light scanning to capture and then generate an anatomically correct 3D computer-generated image of Leonardo's entire exterior; later, the resulting data would be used to create an exact three-dimensional physical replica of the creature. Other researchers could examine Leonardo through a hands-on approach using the resulting casts.

Andersen contacted an industry colleague, Joe Lichko, president of Cubic Vision, and soon they, along with the other scientists, were huddled over Leonardo in Malta, each with an important task at hand. Lichko, who has worked with Andersen in both manufacturing and paleontology, had brought along his proprietary 3D scanning system that he developed over the years.

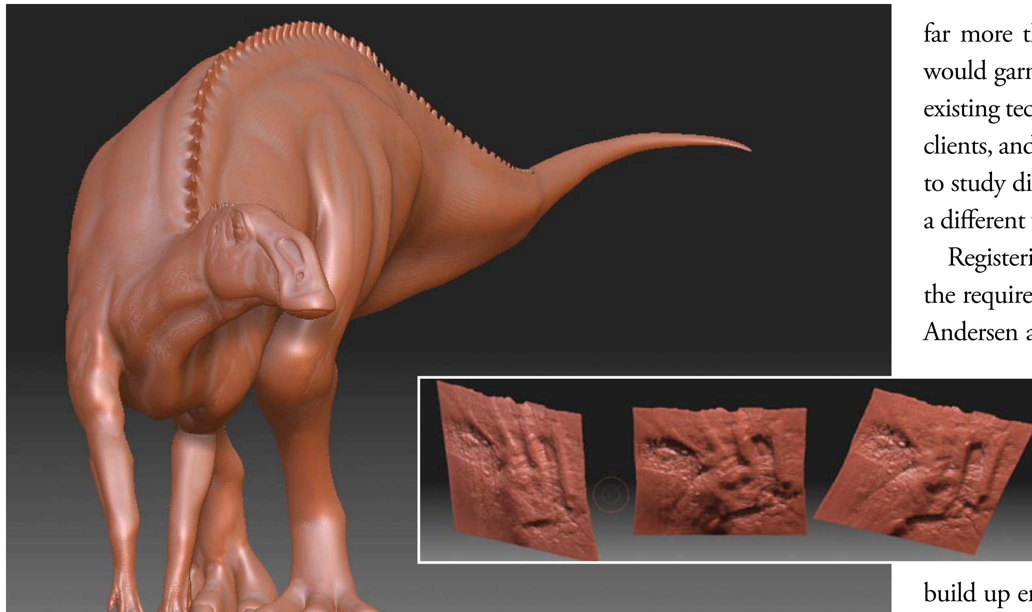
"Leonardo is like a big [piece of] sandstone that is barely held together," describes Lichko. "If you touch him, little pieces would literally fall off, and eventually you would destroy him."

The white-light scanner projects a grid pattern onto the fossil, while a pair of digital cameras on either side of the light-source box map the smallest detail of the surface. What's so unique about Lichko's scanner is that he is able to change the intensity of the light. "There are some very light and some very dark patches on Leonardo, so we were able to stay in the same spot and do multiple scans with different light intensities, and pick up all the features of the dinosaur," Lichko says.

The line-of-sight scanner captures a very flat field over the entire area, meaning that from edge to edge, corner to corner, there is no warping, as there is with many other scanners. This was key, since Lichko did more than 300 scans to get every nook, cranny, and undercut. Each scan comprised an average of 1.4 million points, which was necessary for capturing the fine details of the large specimen: Even though Leonardo was an adolescent, he was still quite large by modern standards. His fossil measures approximately

Digital Imaging

Images by Michael Berglund, Minnefex Inc.



(Above) Artist Mike Berglund had been hired to build a full-size family of *Brachylophosaurs* for a Leonardo exhibit. He sculpted the dino using LightWave for the base mesh and Zbrush for detailing, with the objective of milling the pieces. (Inset) He applied the X-ray images as displacement maps on highly subdivided planes in Zbrush, allowing him to rotate them and clarify the view of the liver-region scans.

eight to 10 feet long, eight feet wide, and two feet high—which required a multitude of scans that had to be pieced together.

"The white-light scans gave us detail down to a grain of sand," says Andersen. Indeed, the accuracy level of the scanner is for a configuration of one-thousandth of an inch. However, the biggest obstacles for this work had nothing to do with the equipment, but rather the subject and the environment, forcing Lichko to come up with an approach that suited this unusual subject. First, the crew had to build a heavy-duty aluminum apparatus from which they positioned a 12-foot bar that spanned the beast. The scanner, which normally sits on a special tripod, was then attached to the bar and positioned as close to the specimen as possible. Second, the structure that housed Leonardo is next to a major railroad line and a fairly busy road with significant truck traffic.

"Each time a train or a truck rumbled by, it would ruin the scan and I would have to start all over," says Lichko of the resulting vibration.

While Leonardo's surface appears fairly smooth, Lichko points out that there are many undercuts. "If you look at his head, for example, there is the eye socket, and you have to move [the scanner] several different ways to capture the interior of that area," he explains. "The little rib bones sticking up, the vertebrae, are shaped like mushroom caps, and the scanner captures most of it, but then you need to move underneath to get it all—underneath, to the side, over the top, and so forth. There are many little areas like that."

As the scanner takes a series of pictures, the software Lichko wrote automatically processes the images into one 3D view. To accurately string the multiple images together into one, Lichko typically places photogrammetry dots on the object. "But we couldn't do that here, so Art [Andersen] and I worked hand in hand, whereby I would do a scan and then send it to Art sitting at a nearby computer so we knew the location from where the scan was taken, and using separate software, we fit each scan into place," he explains.

Pieces of the Puzzle

After a week, the group had nearly 26GB of 3D scan data to edit and piece together—far more than a typical industrial project would garner. Andersen notes that he uses existing technology to work with industrial clients, and then uses that same technology to study dinosaurs. "I'm just applying it in a different way," he says.

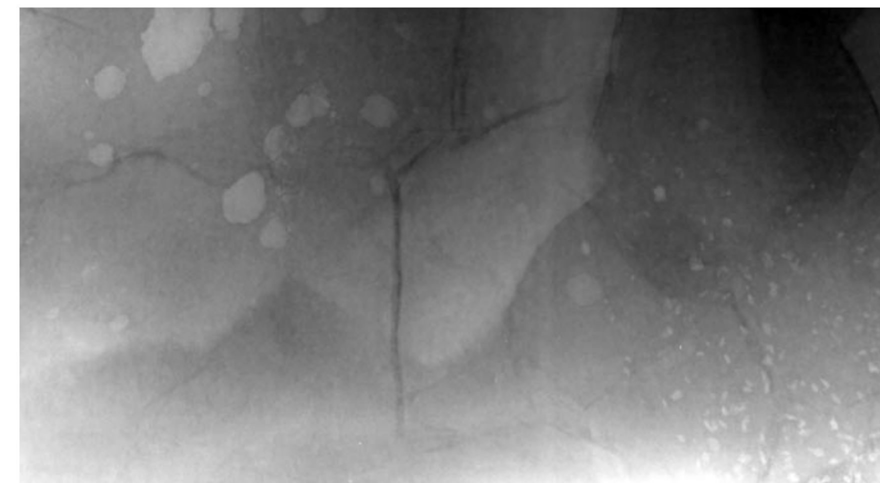
Registering these high-fidelity scans with the required accuracy proved no easy task. Andersen and Lichko started at the center of the specimen and worked their way outward, to minimize the cumulative errors in a single direction. "If you start at the head and work your way to the tail, you build up errors, so the final scans may not line up like they should," explains Andersen. "When we were done with the final scan near Leonardo's foot, which is about five feet away from the starting point, the scans lined up perfectly with zero error."

Lichko's scanner can output the entire polygon mesh, about 75MB (due to overlapping edges for aligning adjacent scans), or it can be done at 10 percent, resulting in a 7.5MB mesh in this case. With the latter option, Andersen was able to properly orient the data, while Lichko scanned the subject. This enabled the two to identify areas of missing information, so those sections could be rescanned. Nevertheless, the mummy contains cracks and missing chunks here and there that result in missing data that cannot be acquired because the original source is missing. For these areas, Andersen had to fill in the data by hand, creating it using Raindrop Geomagic's software.

A close-up look at the unique fossil.

Picture courtesy Great Plains Dinosaur Museum and Field Station.

Using PolyWorks' reverse engineering software and Imageware's Surfacer, an older surfacing program now owned by Siemens, Andersen began the meticulous process of assembling all 300-plus scans, each of which had to align perfectly, before being resolved to within .5mm. "We needed a lot of computer power to do a project like this," Andersen points out. More, in fact, than was available on site in Malta. Therefore, when he had to generate the full-size, high-resolution digital model that would be necessary for rapid prototyping, Andersen was forced to digitally divide the single, blended mesh into eight sections (head, neck, chest, and so forth).



X-rays were used to examine Leonardo's insides. This enhanced X-ray image provides a look to the dinosaur's gut (the pebble-shaped matter is gut content).

To expedite the model assembly prior to rapid prototyping, Andersen also created virtual dowels in the Surfacer software. Finally, he had to generate an STL file (which was nearly half a gigabyte in size) for the 3D printing process.

Indeed, the 3D scan was necessary for prototyping. But, it also provided a 3D volume of Leonardo, which offers a more in-depth look at a subject's anatomy than can be had from a 2D image.

"With this project, we learned we can now create a very accurate model cast without ever touching the surface of the specimen. It can be a 100 percent nondestructive process," says Andersen. "It also gives credence to the possibility of scanning very fragile objects that could never have been scanned in the past through simple modeling and casting." For example, law enforcement could make casts of footprints in the snow at crime scenes. This kind of technology, Andersen adds, also holds potential in proving product liability and patent infringement, as well as for digital inspection of engineered parts and even filmmaking through the accurate reproduction of props.

'Cloning' Leonardo

RP is hardly new—it's been used for years to produce accurate physical replicas of parts in the auto industry and even sculptures by artists, all from 3D computer files. In this application, however, the subject—a dinosaur—proved too large for most facilities. That's when Martin Jones from Ford Motor Co. unearthed a solution.

Jones took the full-resolution data garnered from the white-light scan process and fed the information into the company's prototyping machine, but the output still had to be done in chunks (based on the eight segments Andersen made of the scanned data) due to their dinosaur-size proportions. Later, those blocks were shipped to the Black Hills Institute for assembly.

"We put the pieces together and then molded them as a unit," says the Black Hills Institute's Larson, who was invited to join the project by Murphy. A laser solidified the plastic material that was used to output the prototyped model.

"The material (a photopolymer) they used in the cast was brittle, so we had to be very careful. There were a few slight offsets we had to compensate for in the data; with something like this, you cannot get it absolutely perfect," Larson says. "There was a mesh going across the entire surface of the fossil, so you are going 10 feet across from one registration end to the other; in some cases, there was a bit of discrepancy, maybe one-tenth of an inch, where we would have to build up a little clay to make a bridge so you wouldn't see the seams."

Unfortunately, the digital volume was not complete, as the group was unable to scan the downside (the side the dinosaur was lying on when he died) due to the visual obstructions resulting from the steel structure and the plaster jacket that had been supporting Leonardo since he was excavated. Because rapid prototyping requires a solid output, the information has to be present in the computer file. Andersen fixed this problem by meticulously adding a base and sides to the data prior to the parts being prototyped.

According to Larson, creating a RP clone of the dinosaur enables scientists and paleontologists to be more hands-on while studying it, since the original fossil is much too delicate to touch—and much too valuable to become extinct right before their eyes.

"When you look at Leonardo, he is a mottled color, sandstone, and when you bring a scan in, it typically is an artificial color of some sort. You can see more features in the artificial color, and things pop more, like the tendons in his back and the skin impressions," says Cubic Vision's Lichko. "He is amazing and unique."

A crew at the Black Hills Institute preps the rapid-prototyped model of the prehistoric beast.

Larson agrees. "We can see textures of wrinkles in the skin, and there appears to be some muscle preservation, as well. You can see areas on the shoulder that look like they were preserved in the shape of the original muscles. Maybe there is still some soft tissue left; maybe, though we do not know for sure yet," he says. "But certainly what is left there is something left by the soft tissue, whether it is bacteria that created chemicals that made those muscle shapes or muscle tissue itself. We do not know because we have not done any destructive tests on him."

Additionally, the RP model enables other museums to exhibit the rare find, augmenting their display with perhaps CG animations and information about the beast's prehistoric past and the scientific procedures it has undergone in more recent times. And this is something that Larson is especially interested in.

At the Black Hills Institute, Larson and his colleagues not only discover, collect, and clean fossils, but they also prepare them, make replicas through the usual molding and casting process, and mount them for museums worldwide. Research also plays a vital role in what they do.

"When kids see the prototyped Leonardo and scientists study it, they basically see the same thing as they would by looking at the original bones, at least as far as the surface detail goes," Larson says.

In fact, scanning and RP have been used before to "complete" a dinosaur skeletal mount in which the left side of a jaw may be present but the right side is not, for instance. The process will accurately duplicate the part; presenting the beast whole gives people a better understanding of what it looked like, a shape.

In fact, Larson and his group are currently doing just this to produce a completed skull of a new species of dinosaur. "We don't have a complete skull, but we do have enough parts, such as rights and lefts. If we prototype the missing pieces, it will give us a whole skeleton to articulate properly, to offer a better visualization of what it looked like," he explains.

Presently, the prototyped model of Leonardo is on exhibit at the Phillips County Museum in Malta. Casts made from the prototype are at the Judith River Dinosaur Foundation and the Black Hills Institute. Smaller-sized versions of these precise models also have been made for various purposes.

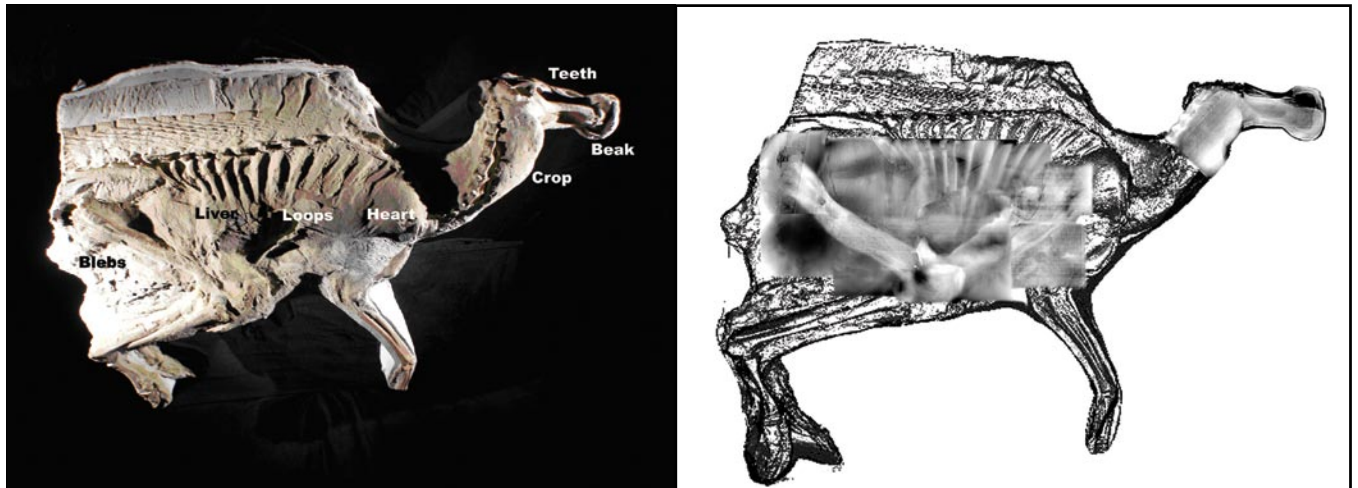
"We live in a wonderful age where we can take what we know about electronics and use it on animals that have been dead for 70 million years or more. Using all these wonderful advances in medical technology and computer technology, and other technological advances, we can do some things with fossils that we never thought possible," Larson says. "In fact, we are finding out that the fossilization process preserved a lot more than just the bones of that animal. Originally, we didn't even think they were bones, but that they were replaced with something else—until we did X-ray refraction and found they really were bones. We are discovering more

Perfectly Preserved

Leonardo officially has been deemed the best-preserved dinosaur remains in the world by Guinness World Records, with approximately 90 percent of his body covered in fossilized soft tissue.

Most dinosaur fossils contain only bone fragments of these long-ago beasts. That's because in this period where every creature fought for survival, hungry scavengers often ran away with chunks of a fallen creature in their mouth and belly. Even more rare is finding a dinosaur that is mummified, since bacteria and other decomposers would further break down the carcass.

So how did Leonardo survive the tests of time? Scientists theorize that immediately upon his death, the dinosaur's fresh corpse became submerged and covered in silt, staving off the decomposition process. Eventually, the corpse became mummified and fossilized, with tiny pieces of sand replacing preserved tissue.



To properly interpret the X-ray images, the team assembled them in their recorded positions (right) creating a mosaic. The image at left contains labels showing the various regions.

and more about the fossilization process and what it takes to make a fossil, thanks to these technologies. They give us a better understanding about ancient life and how much it has changed, and how little it has changed."

X-ray Vision

Through scanning and RP, the crew was able to obtain a detailed look at Leonardo from the outside. However, they were especially interested in what an internal examination would reveal. While a CT scan would have provided a three-dimensional view, no machines were available at the time to handle a patient of this size. A CT scanner at Hill Air Force Base in Utah was a possible option, but the fragile fossil would have had to have been situated at an odd angle for the process.

Andersen spoke to colleagues he worked with on industrial projects, and eventually another option was unearthed: a CR (Computed Radiography) system from Kodak, which produces X-ray images using a special plate and source that can be scanned into a computer and modified for optimal viewing.

Prior to joining the science team as they conducted their two-week digital autopsy in Malta, Steve Mango, a technical expert on Carestream Health's (formerly Kodak's) Non-Destructive Testing team, first tried out the technology in the Kodak lab in Rochester, New York, using a small piece of Leonardo that had broken off from the main fossil. "We could see some of the types of things they were looking for. We could differentiate the bone from the surrounding matrix, and although it didn't look like much to me, when I sent the group the sample images, they were very excited and asked if I would come to Malta," says Mango. And he did, taking a portable CR system with him.

Mango's task, which he shared with his colleague, Steve Mazur (now deceased), and the NDT Group from Grand Rapids, Michigan, was to X-ray Leonardo to see what, if anything, was inside the fossil, to find out how the bones were articulated, and, most importantly, to determine whether or not they could find any remnants of internal organs. "Between all of us, we were able to pull a lot of good shots and get good sensitivity and nice quality images that really wowed the scientific team," says Mango.

CR utilizes the same X-ray but more powerful gamma sources (Iridium-192 and, eventually, Cobalt-60) as conventional radiography. In essence, the more powerful the source, the deeper the X-ray penetration. However, unlike a typical X-ray, it has a reusable plate instead of film to retain a latent image. A reader then uses a red laser to scan the image, which causes it to luminesce in blue light wherever the stored X-ray energy is in direct proportion to the amount of stored energy. "Basically, you get a higher pixel value with a higher dose of radiation, and it's all digital," says Mango. Once the image appeared on the computer screen, the experts used cutting-edge image-processing techniques for a clearer picture of what lied within the dense rock that is, essentially, what's left of Leonardo.

Once again, the group had to apply knowledge they had garnered from industrial-engineering applications (looking for buried conduits and pipes in concrete structures, for instance) to paleontology. "In some respects, it wasn't so different—we were looking inside a structure for hidden features," says Mango, "but it just wasn't something I or Steve had experience with. So we were learning as we went along," in terms of getting the optimal source dose and exposure time for this unique subject. As Mango points out, the exposure time was as long as two-and-a-half hours for the most challenging shots.

Mango does not believe anyone has X-rayed a dinosaur before, and what made this project so challenging was Leonardo's thickness, which required a great deal of energy to penetrate. While the Iridium and Cobalt are high-energy sources and can achieve the desired penetration, the trade-off is they produce lower-quality imagery in terms of detail and sharpness than a typical X-ray with a less-potent source. Another hindrance was the steel frame supporting Leonardo. A welder was able to remove some of the braces, but some still had to remain, as did the plaster matrix used to prep and protect the specimen.

"The matrix was an irregular shape, and it was in the way. We had some difficulty discerning what is really the dinosaur fossil versus the surrounding rock matrix and plaster," says Mango. "That is where the expertise of the imaging experts, such as Andersen, comes in. They are able to work around obstacles like that."

While the scientific team was hoping to see certain organs, such as the heart and the chambers of the heart ("Their expectations were sky-high," says Mango), the jury is still out as to whether those organs are present. Mango and the others agree that there appears to be some evidence of organs as well as artifacts in the digestive track. "Eventually we might have been able to perfect the techniques a little more, but I am not sure we would ever have been able to get a better view given the limitations of the specimen and how radiography works, how the rocks scatter the X-ray beam and such," Mango notes.

Nevertheless, the team was indeed happy with the results, which showed great promise, thus whetting their appetites for more information. Some time after the initial forensic examination and seven years after Leonardo was discovered, he was transported to the NASA Ellington Field nondestructive testing lab for further X-rays that once again used a Cobalt-60 source. There, some of the steel structure was removed and heavy wooden supports were added to the perimeter, as to not block the X-rays.

While looking at the X-rays in Houston, the group encountered a prehistoric mystery: They had noticed, for the first time, that some of Leonardo's ribs were missing, but they couldn't figure out why. Perplexed, Andersen examined the outside of the dinosaur more closely.

"We hadn't noticed that Leonardo had been bitten. You should be able to look at him and realize there is a bite mark on his side, but no one ever did," says Andersen. In fact, upon further examination, Andersen noticed that the ribs were not missing, but hung from a big flap of skin and flesh that was now on the dinosaur's belly side. "You can see the rib bones there and part of the stomach," he describes.

"At first, they thought, 'No, it can't be,' and when they looked at him some more, they said, 'You're right. He was bitten,'" Andersen further recalls. This led the scientists to hypothesize that the dinosaur had been attacked and mortally wounded prior to death.

Bone of Contention

When Nate Murphy found Leonardo, he unearthed the find of his lifetime. Unfortunately, the dinosaur no longer belongs to him, but is the joint property of the Judith River Dinosaur Institute, which he founded in 1993 but is no longer associated with, and the Hammond family, whose land the fossil was found on.

This past May, Murphy was sentenced to 60 days in jail and was issued a monetary fine for stealing a raptor fossil from private land in the Malta area. This month, he is expected to be sentenced on a federal charge also involving the theft of fossils from federal land. He pled guilty to both charges, and signed over his portion of Leonardo to the Institute.

For some time, Leonardo had been exhibited at the Houston Museum of Natural Science, but is being shipped back to Malta to a new museum there.

It's Elemental

In addition to the X-ray and digital scanning processes, the scientists conducted an elemental scan on Leonardo's forearm that had broken off. Paleontologist Pete Larson and chemist Bob Morton took the arm to Stanford University, where researchers used a linear accelerator to produce an X-ray fluorescent image, or elemental scan, of the fossil piece.

The machine scans the surface of the object, and a camera registers and records the results as a 2D image based on the heavier elements present—calcium, phosphorous, potassium, iron, cobalt, and so forth. The scientists rotated the arm seven degrees and did another scan, resulting in a 3D false-color image. According to Larson, the polarizing light for the 3D image of the elemental scan enables the group to see the topography of the specimen, along with the chemicals present. Thus, the image on the computer screen will show a mixture of these colors, one for each element found, and in the corresponding concentrations.

"The idea is that you can see a pattern on Leonardo, and you get a good idea of what color his skin was, since certain elements give off specific colors," says imaging expert Art Andersen. For example, copper sulfate results in a blue hue.

"This is brand-new science," Andersen points out.

While the outcome of the arm didn't reveal all that much, the group believes that another body part, such as the chest, could show far more.

Digital Imaging ■ ■ ■ ■

Looking at a Prehistoric Star

In all, 130-plus CR X-rays were taken of Leonardo, but the group needed a much clearer picture of those X-rays, and Tom Kaye was able to give the scientists just that. Kaye, an associate researcher with Burke Museum in Seattle, had a long history of processing astronomical and microscopic images with advanced techniques and software similar to that used on the Hubble Telescope. Andersen and the team sent the foggy-looking X-rays to him, and he worked his digital magic, which he had done so often in the past on both galaxies and dinosaurs.

"Leonardo was a few feet thick, and when you X-ray something like that, you have to hit him with a lot of X-rays to penetrate the subject. The problem is you lose detail in the image because of the bright X-ray source you are using. You end up getting an image that sort of looks like a cloudy blob," explains Kaye. "So the original images that came out of the X-ray process didn't show much detail."

The group was looking to see if there were any details, such as internal organs, preserved inside the specimen. All they could see were faint hints as to what was inside. "The problem with the images was that a large portion of the dynamic range was taken up in these big, cloudy blobs," says Kaye. "The details were superimposed on these big curves of dark and light areas, and they were completely obscured. So my task was to selectively remove these large gradients in the image while preserving the small details."

In a process that took more than a week, Kaye used several software tools to do a specific form of unsharp masking to create an even fuzzier image of the existing X-ray—one that has no detail, just the large gradient. Then, he subtracted that result from the original image. "So you are, in effect, taking out the rolling hills and valleys, and you are leaving the details of what is sitting on those hills and valleys on a flat plane," he explains.

Next, Kaye leveled out the entire gradient, using software that is often used to remove the haze present in a fuzzy image of a galaxy to reveal stars. "It removes the fuzz and leaves the points of light," he says. In this case, after Kaye was done, what had been blurry little objects on the X-rays were now dinosaur ribs, for instance.

The challenge for this evolutionary project resulted from the number of generated images, each of which had to be tweaked one at a time, pixel by pixel. Then, each image had to be pieced together into a mosaic, so that every image visually compared with those adjacent to it.

At one point, Kaye and Andersen decided to try something unique and created some stereo imagery from the 2D X-rays. While at Houston, Andersen built a special gantry that allowed the group to change the angle of the X-rays to achieve 3D convergent stereo pairs. "Unfortunately, we didn't get enough of that done because each X-ray exposure took too long, and we couldn't produce enough pairs," says Kaye. However, the few that were available held promise for future applications in which CT scans are not possible.

In the end, all the X-rays were aligned to show, for the first time, the internal structure of a dinosaur—the leg bones, the head rolled over to the side, the neck, and the teeth. "You are looking at the dinosaur as he actually was in real life," says Kaye. "We mount these skeletons in museums, but that is usually our best interpretation of how they were. In this case, we could see the exact way nature had put him together."

Kaye credits this accomplishment to computers and the latest advancements in image processing. He points out that the industry is making so many strides in digital imaging that this type of work finally is available to others beyond NASA. "It's a very exciting time in this field," he adds.

Image by Joe Raffa, Plastic Thought Studios.

Artist Joe Raffa generated this CG animated scene of *Brachylophosaurs* for a documentary about Leonardo titled *Secrets of the Dinosaur Mummy.*

A Past Life

So, what did the enhanced X-rays of Leonardo's insides reveal? "There were several things we saw in the X-rays that gave us hints that maybe there were things preserved inside the dinosaur," Kaye says. "It will take a little bit more technology to go in there and find out exactly what those things are, but certainly they did show there were structures inside the rib cage of the dinosaur that were preserved over many, many millions of years."

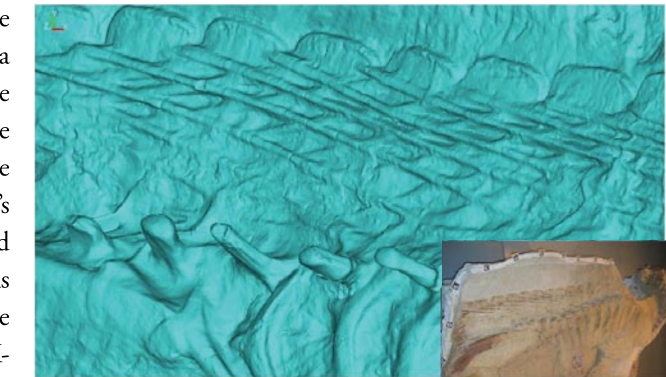
After the X-ray enhancements, the scientists could clearly see how the skin laid on Leonardo's body. They could see the orientation of his bones. "This is so rare," says Kaye. "One of the misconceptions people who are not in paleontology have is that every time a dinosaur skeleton is found, it looks like what they see in a museum. That is not the case. The only reason why you see these articulated dinosaurs on TV is because they are special. We have been looking for fossils in Wyoming for 15 years, and we have never found a dinosaur that even had a complete pair of legs, let alone a complete skeleton."

Furthermore, the X-rays reveal the contact line of the keratinous beak, where it started and where the skin ended. "The beak climbs up the nose bridge much farther than we had imagined," states prominent paleontologist Bob Bakker, who was present during the processes in Malta and Houston, and during the documentary filming.

The imagery also enabled the scientists to map the complex digestive path—from the throat through the intestines—after uncovering what they believed to be undigested food. "He was a high-fiber chewer and processor of the toughest plants in the ecosystem," says Bakker, "which explains why duckbills had been so successful for such a long time."

For now, one of the most impressive occurrences was when the group looked at the dinosaur's intestines—a first for them. "We have 3D soft tissue structures inside the visceral cavity of an almost full-grown dinosaur," Bakker further states.

But, did the group find the Holy Grail: a heart and liver? The scientists cannot be sure, though they do believe that they located the region where the heart may be, though a better resolution image is needed to determine this with a high degree of certainty. Andersen's presumption is based on the fact that regions rich in iron would be more dense to the X-rays than other areas of fat and muscle. "We did find some fuzzy areas where maybe the heart and perhaps the liver could be. A CT scan might reveal more."



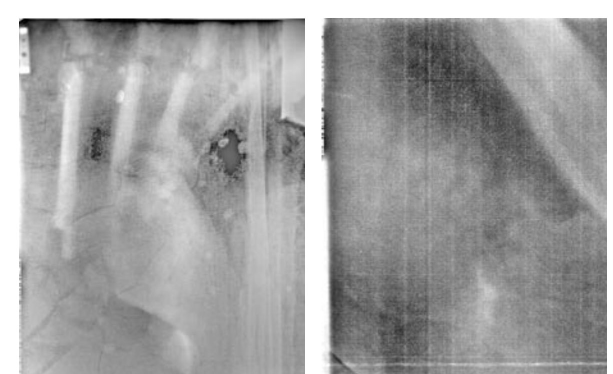
Above is a low-resolution scanned image depicting the dinosaur's tendons and vertebrae; inset shows the region on the fossil.

Larson has located a CT scanner that might be able to handle a scan of Jurassic proportions, but it is currently dismantled and is awaiting shipment to a new location, possibly in Europe. Wherever the device ends up, the problem then becomes shipping the fragile Leonardo to the locale—a difficult but not impossible task, says Larson.

Bakker, in the documetary film, summed up the situation well: "We are awash in a sea of clues. We definitely have something going on there."

What is certain is that the high-tech images of the internal and external structures have brought the world closer to a living dinosaur than it has ever been.

For now, the group continues to study the imagery, and there is even discussion about taking core samples, although Andersen would rather wait and let technology get further ahead.



(Left) The area were the liver should be located appears in the lower center of the image. (Right) The white image in the lower center is the most probable location of the heart.

"Leonardo is so rare, and we really do not want to perform any kinds of invasive tests that we would regret in the future," Andersen says. "After all, we cannot go back once the damage has been done. While some suggested that taking core samples by cutting into the dinosaur would offer more definitive answers as to whether a heart and liver are present, I would rather wait and eventually try to get a good CT scan rather than do the probes and then look back and ask, 'Why did I ever do that?' That happens now as we look back on work that was done 50 to 100 years ago."

Andersen offers up the Smithsonian's 100-year-old *triceratops* as an example of destructive methods: Steel pipe had been cemented into the fossilized bone. In contrast, the Chicago Field Museum's more recent Sue, said to be the most complete and best preserved *Tyrannosaurus rex* specimen ever found, contains a steel armature structure attached to the outside of the bone, not through it. So, as new technologies become available, the fossil could be studied further.

"I hope that what we have done here will inspire other high-tech and scientific work on dinosaurs, including further study of Leonardo," says Andersen. "I hope to see more and more digital scanning of fossils as time goes on. People love dinosaurs, but there is not a lot of funds available for this type of work, unfortunately."

For the time being, though, the group is content that it has created the world's first anatomically correct dinosaur, and in doing so, changed the field of paleontology forever. ■

Karen Moltenbrey is the chief editor of *Computer Graphics World.*