

4 Longmen Grottoes in Digital Light



Editor's Note:

"Among the four suburbs of Luoyang, the finest scenery lies at Longmen." Tang Dynasty poet Bai Juyi wrote these lines more than 1,200 years ago. Standing on the bank of the Yi River in Henan, central China, he saw the same cliffs we see today.

The Longmen Grottoes consist of 2,345 caves and niches housing nearly 110,000 Buddhist statues, and more than 2,800 inscribed steles. They have stood here for over 1,500 years. The chisels that carved them fell silent long ago, but the stone remembers. In November 2000, the Longmen Grottoes were inscribed on the UNESCO World Heritage List. "The grottoes and niches of Longmen," the committee wrote, "represent the high point of Chinese stone carving."

That judgment stands, but standing is not the same as enduring. Water seeps, wind erodes, and the stone has also suffered at human hands. In the past, conservation used to mean intervening after damage. Today, it means anticipating it and preventing it. Technology has made that shift possible. It answers a fundamental question: How do you keep "alive" something that is older than any living memory and made of stone?

This special edition follows Camilla Quaranta, an Italian student at Henan University, and Li Xiawei, a young guide at Longmen, as they discover the technologies reshaping how the site is conserved and experienced today.

Keeping Cultural Heritage Forever Young

In AD 500, after the Northern Wei Dynasty's relocation of its capital to Luoyang, construction began on a massive state project in the Yique Mountains located south of Luoyang. This was the Binyang Middle Cave, the only royal grotto at Longmen whose construction process is explicitly chronicled in official historical records.

More than 15 centuries later, an Italian student stood before it. Camilla Quaranta grew up in Milan, where she often visited museums and old churches with her family. Those early encounters with Roman relics and Renaissance art sparked a lifelong love of history. Now studying at Henan University, she came to China with a particular curiosity: to see for herself how an Eastern civilization, so different from her own, has endured over time. Longmen Grottoes was one of her stops.

Her friend Li Xiawei, a young guide at the grottoes, accompanied her into the cave. "Welcome to wonderland," Li said.

They looked up at the dome. A giant double-petal lotus has been "blooming" there for over 1,500 years. Around it people can see a blur of celestial musicians, whose colors and outlines have long faded.

"What did it look like when it was first built?" Camilla wondered quietly. In the past, one could only imagine. Today, using a combination of advanced technologies, the research team at the Longmen Grottoes Academy has digitally recreated the original appearance of

the lotus caisson.

To achieve a scientifically thorough restoration, the team first collected high-precision 3D data of the lotus caisson in January 2021, delineated its contours on orthophoto maps, and produced outline base maps. Due to prolonged damage from water seepage, weathering, microorganisms, and other factors, the painted surface had largely flaked off. Researchers could see only red, black, and a few green traces with the naked eye.

With portable microscopes, they also observed yellow, blue, pink, and white. They used X-ray fluorescence analyzers and laser Raman spectrometers to sample and test pigment residue from different parts of the caisson, identifying the pigment composition and establishing the overall color scheme.

After more than a year, the deteriorated lotus caisson was reconstructed on a flat surface. Then in early 2024, building on the results, the Academy released an animated version. Camilla and Li finally saw a more lively scene: celestial musicians stepping on clouds, soaring through the air, playing musical instruments and dancing, their fluttering sleeves evoking a joyful atmosphere.

"We do not have to time travel," Li said. "Now, through digital technology, everyone can see what they originally looked like."

Moving south, they arrived at the Ten Thousand Buddhas Cave, a Tang Dynasty cave named for the 15,000

small seated Buddhas carved into its walls. On the south wall of the front chamber stands a damaged statue of Guanyin, known in Sanskrit as Avalokitesvara. The head and arms of the statue are missing.

Li showed Camilla an old photograph of the undamaged Guanyin. Based on that, the team created a digital version in which the face, robe and decorative ribbons have been restored, reflecting the original appearance.

"Will I ever see a statue like that again?" Camilla asked. "I think so. In the digital world," Li replied. Camilla wanted to understand how this was done. Li took her to the Academy, where they met Zhang Guofeng, deputy head of the Exhibition and Digital Section.

Zhang told them the Academy's digital work began 20 years ago with the "Longmen Grottoes 3D Digitalization Project." In 2021, the team launched a new phase, conducting high-precision data collection for representative caves to create comprehensive digital records. Unlike earlier methods like drawing, molding, and black-and-white photography, the latest 3D scanning can achieve millimeter-level accuracy without touching the artifacts.

For the Guanyin statue, the first step in virtual restoration was finding evidence, Zhang said. Drawing on historical photographs, academic research, 3D digital technology, color analysis, and traditional sculptural knowledge, the team virtually restored the statue

and its original colors.

"Virtual restoration isn't about making it 'look complete,'" Zhang said. "It's about getting as close as possible to what it originally looked like. That distinction matters."

When Camilla asked about the "authenticity" of digital restoration, Zhang said, "Digital restoration is more a form of witnessing, more about the process. Cultural relics are cultural relics. Virtual restoration simply allows people to see what these relics looked like before they were damaged. It is a form of conjecture and verification."

For Zhang and his colleagues, the goal of digital restoration goes beyond freezing a moment in time. It is about keeping the artifacts "alive," preserving their information before further decay and carrying their presence beyond the cave walls, into spaces where stone cannot travel.

Today, through AR technology visitors to Longmen Grottoes can view the figures as they originally appeared by pointing their smartphones at the damaged statues.

"This is just the beginning," Camilla said, looking at the restored image on the screen. "What moves me most is seeing the past come back and knowing that these grottoes can now travel to classrooms, museums, and screens anywhere in the world. They no longer belong only to this mountain. They belong to anyone who wants to see them."

Watching Over the Stones:

A Preventive Approach

To most visitors, the Fengxian Temple, the largest cliffside niche shrine at the Longmen Grottoes, is a great option for taking photos. To the researchers at the Longmen Grottoes Academy, it is a precious heritage to guard carefully, where every crack and damp patch is a symptom demanding immediate attention.

The temple houses the Vairocana Buddha, the tallest and most artistically accomplished statue at the site.

Water infiltration has been a persistent threat for over a millennium. Just above the southern slope of the temple sits a karst cave. Because limestone is highly soluble, water seeped through the stone, shaping the cave's stalactites and stalagmites over thousands of years. It also threatened the precious stone statues below.

Fan Zilong, who heads the Protection and Restoration Section at the Academy, said as early as the Tang Dynasty (618-907), ancient craftsmen dug drainage channels above the Fengxian Temple to prevent seepage from eroding the great Buddha. More than a thousand years later, this system is still functioning. "The ancient craftsmen's site-sensitive wisdom is an inseparable part of the cultural heritage itself," Fan said.

Yet managing water infiltration still remains one of the most difficult challenges in grotto conservation. The ancient channels could do only so much. What was needed was a way to detect problems before they became disasters.

That was where modern technology stepped in. Field inspections that used to take Fan and his peers two weeks can now be done sitting in front of a computer, reviewing real-time data from key monitoring points. "It is like taking a patient's blood pressure and checking their blood sugar and lipids," Fan said.

The monitoring system tracks three main dimensions, each marked in a different color on the dashboard: the atmospheric environment, the cave micro-environment, and the cultural

relics themselves. Atmospheric monitoring tracks temperature, humidity, rainfall, and wind speed, while the cave micro-environment monitors internal temperature, humidity, and wall temperature. Together, they paint a complete picture of the grotto's "health."

The system proved its worth during the torrential rains that hit Luoyang in July 2021. "We were staring at the screens day and night, monitoring every change," recalled Liu Yi, a member of the team. Thanks to the early warning system, they noticed abnormal readings from crack displacement meters at the south cave of Leigutai, a group of three parallel caves and niches. "The data showed structural instability after the heavy rain. Without timely reinforcement, there was a real risk of collapse."

The team rushed to the site and installed emergency shoring, reinforcing the exterior with steel supports and adding bracing inside. And then came an unexpected reward. When they later dismantled the front wall, they discovered an 80-centimeter gap hiding more than 80 relic fragments. "The most exquisite piece was a Buddha head from the Tang Dynasty," Liu said. In responding to one emergency, they had uncovered a hidden treasure.

For Fan and Liu, however, the real significance of this work lies not in any single discovery, but in a fundamental shift in conservation philosophy — from reactive, emergency interventions to preventive care. The monitoring platform is not just a tool; it is a new way of thinking about stewardship.

"Just as people today pay attention to their health and get regular checkups, monitoring allows us to detect problems early and intervene before they get worse," Liu remarked.

In the end, the true guardians of Longmen are not the sensors or the screens. They are the vigilant minds behind them. Their goal is not simply to repair the past, but to safeguard it for the future.



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Guardians Across Time:

How Technology Helps

The Cultural Relics Science and Technology Protection Center at the Longmen Grottoes Academy, may be likened to a hospital. Only, the "patients" here are of stone and the "doctors" do not use scalpels. Their tools of choice are laser cleaners, electron microscopes, and 3D printers. These guardians of history have young faces, yet their steady hands carry a quiet resolve belying their years.

Rui Zihang, born in 1995, guides a laser cleaner over a stele made during the Northern Qi Dynasty (AD 550 – 577). As the beam sweeps across the stone, the black grime encrusting it peels away layer by layer, revealing the grey-blue surface beneath. Gradually, the intricate folds of a carved robe emerge.

"It uses thermal effects," Rui says, keeping his hand steady on the device. "Different materials absorb specific frequencies at different rates. We just heat the contaminants until they separate,

leaving the underlying stone unharmed."

This non-contact method leaves no marks, making it safer than traditional techniques. But precision requires patience. Before touching the stele, Rui has spent hours testing the exact wavelength and energy on a hidden corner. Too little energy will leave the grime stubbornly intact. Too much risks scarring the ancient surface.

Asked why he chose this job, Rui pauses and looks at the stele. "Our job is to restore the artistic and cultural value of these historical relics as much as possible," he says. "Seeing these remnants of the past naturally inspires a sense of awe. You can't help but imagine how magnificent they once looked. It is a dialogue with history, and the process itself is healing."

In a nearby lab, Ma Jieyi, another young staff at the center, is using a small sandblasting device to clean the surface deposits on a Buddha head. In

another part of the room, a 3D printer is printing a replica of another Buddha head, layer by layer.

Ma picks up an earlier test piece. It is a 3D-printed model of a grotto eave. Over the centuries, the original eaves collapsed. The printed pieces can fit precisely into the gaps to block rainwater and the accompanying erosion. On the table lie fragments of a relief, the Emperor Worshiping the Buddha. Fresh out of the printer, it is off-white in color. Only after meticulous coloring will it truly resemble the historical original.

Turning digital models into physical prints is a matter of size and precision. Ma says small pieces take only a few hours, while larger ones need 16 or 17 hours. Each piece is different, and each demands its own approach.

If 3D printing reveals the external form of the Buddha, then scanning electron microscopy peers inside.

Zhang Man, also a member at the center, operates a scanning electron microscope. On the screen, a stone sample the size of a fingernail is magnified tens of thousands of times, revealing mineral crystal structures, weathering cracks,

and particle deposits. The high-powered microscope can detect structures invisible to the naked eye and ordinary optical microscopes.

"By observing the microscopic structures, we can analyze the chemical composition of the artifacts and detect tiny cracks that are otherwise undetectable," Zhang says.

She adds that one of the most common types of damage is due to weathering. Unweathered artifacts have a dense structure. After weathering, the structure becomes loose, cracks appear, and porosity increases. The scanning electron microscope helps identify the causes of deterioration, providing a basis for developing conservation plans. "For a more rigorous and evidence-based assessment," she adds, "we need to combine this with other testing methods."

The technologies are only half the story. Behind every laser beam and every data point is a young conservator who has devoted years to understanding stone, water, and time. In their hands, technology becomes something more than machinery. It becomes a form of reverence.



The Fengxian Temple at Longmen Grottoes in Luoyang city, Henan province in central China. (PHOTO: VCG)