FEATURES

SAVING GRACE

Scientists are leading Notre Dame's restoration—and probing mysteries laid bare by a fire

By **Christa Lesté-Lasserre**

In a 2019 fire, Notre Dame's spire toppled and pierced its vaulted ceiling. Its lead roof melted into jagged stalactites.

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Eight restoration scientists put on hard hats and heavy-duty boots and stepped inside the blackened shell of Notre Dame de Paris, the world's most famous cathedral. Ten days earlier, a fire had swept through its attic, melted its roof, and sent its spire plunging like an arrow into the heart of the sacred space. Now, it was silent but for the flutter of house sparrows. The space, normally sweet with incense, was acrid with ash and stale smoke. Light beamed through voids in the vaulted stone ceiling, cutting through the gloom and illuminating piles of debris on the marble floor.

Yet the scientists, called in by France's Ministry of Culture to inspect the damage and plan a rescue, mostly felt relief—and even hope. Rattan chairs sat in tidy rows, priceless paintings hung undamaged, and, above the altar, a great gold-plated cross loomed over the *Pietà*, a statue of the virgin Mary cradling the body of Jesus. "What matters isn't the roof and vault so much as the sanctuary they protect," says Aline Magnien, director of the Historical Monuments Research Laboratory (LRMH). "The heart of Notre Dame had been saved."

On 15 April 2019, an electrical short was the likely spark for a blaze that threatened to burn the 850-year-old cathedral to the ground. Following a protocol developed for just such a disaster, firefighters knew which works of art to rescue and in which order. They knew to keep the water pressure low and to avoid spraying stained glass windows so the cold water wouldn't shatter the hot glass.

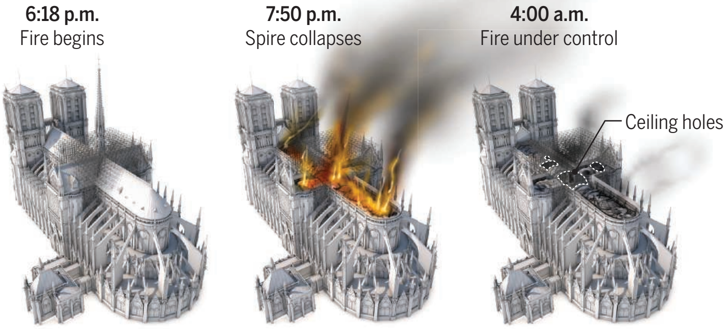
But even though their efforts averted the worst, the emergency was far from over. More than 200 tons of toxic lead from the roof and spire was unaccounted for. And the damage threatened the delicate balance of forces between the vault and the cathedral's flying buttresses: The entire building teetered on possible collapse.

At LRMH, the laboratory tasked with conserving all the nation's monuments, Magnien and her 22 colleagues apply techniques from geology to metallurgy as they evaluate the condition of Notre Dame's stone, mortar, glass, paint, and metal. They aim to prevent further damage to the cathedral and to guide engineers in the national effort to restore it. President Emmanuel Macron has vowed to reopen Notre Dame by 2024, and he has appointed a military general to lead the operation, which involves many government agencies and has drawn philanthropic pledges of about €1 billion. But it is the LRMH scientists who lead the critical work of deciding how to salvage materials and stitch the cathedral back together. And even as they try to reclaim

Baptism of fire

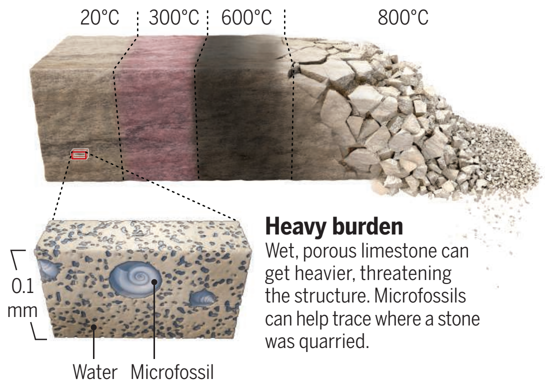
The 850-year-old Notre Dame cathedral nearly burned down on 15 April 2019. Researchers are figuring out how to salvage materials and restore the Paris icon. The fire also offers a window to the cathedral's past by exposing materials that were largely off-limits to science.

Graphic by **Chris Bickel**



Color code

Heat transforms iron compounds within limestone and weakens it. Associated color changes hint at whether fallen stones can be reused and where the structure is vulnerable.

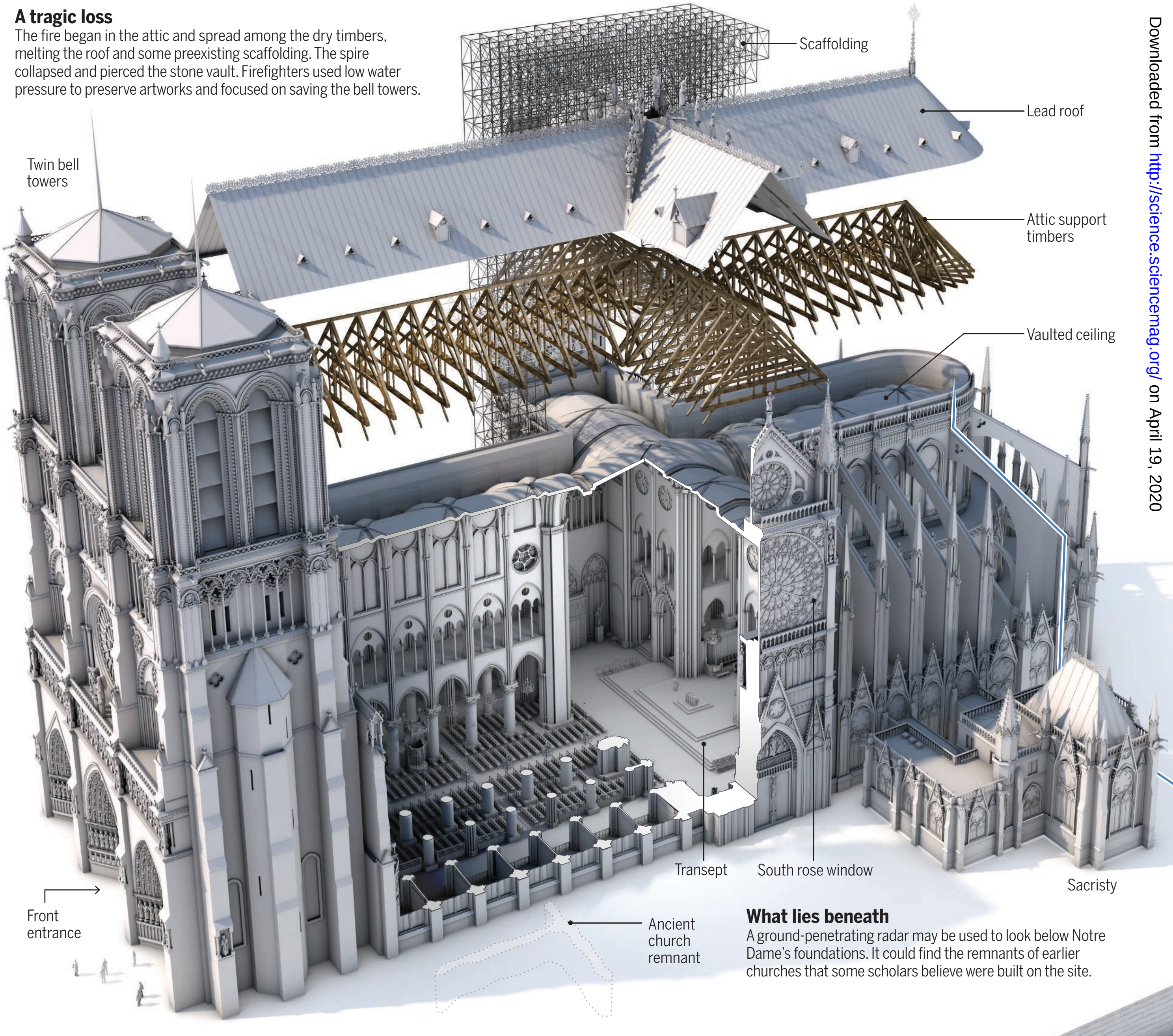


Heavy burden

Wet, porous limestone can get heavier, threatening the structure. Microfossils can help trace where a stone was quarried.

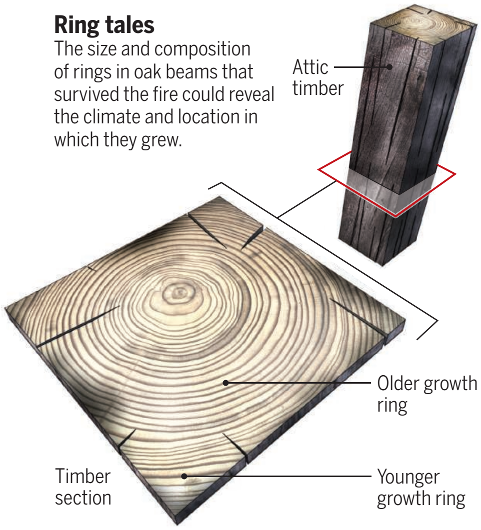
A tragic loss

The fire began in the attic and spread among the dry timbers, melting the roof and some preexisting scaffolding. The spire collapsed and pierced the stone vault. Firefighters used low water pressure to preserve artworks and focused on saving the bell towers.

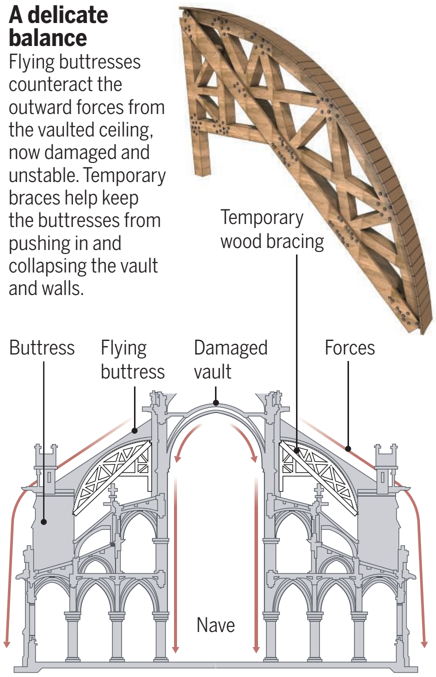


What lies beneath

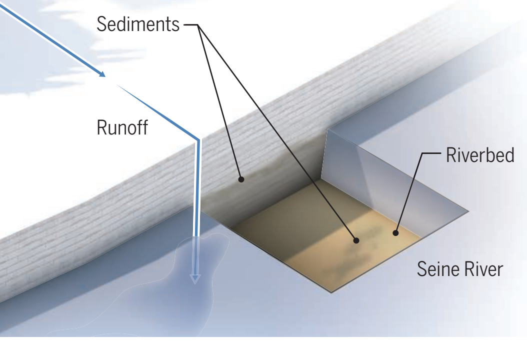
A ground-penetrating radar may be used to look below Notre Dame's foundations. It could find the remnants of earlier churches that some scholars believe were built on the site.



Ring tales
The size and composition of rings in oak beams that survived the fire could reveal the climate and location in which they grew.



A delicate balance
Flying buttresses counteract the outward forces from the vaulted ceiling, now damaged and unstable. Temporary braces help keep the buttresses from pushing in and collapsing the vault and walls.



A tainted legacy?
Lead aerosols from the roof and spire caked the cathedral in contamination. But runoff from the roof may have polluted the Seine River for centuries. Researchers will look for lead with Notre Dame's signature in river sediments more than 100 kilometers downstream.

what was lost, they and others are also taking advantage of a rare scientific opportunity. The cathedral, laid bare to inspection by the fire, is yielding clues to the mysteries of its medieval past. "We've got 40 years of research coming out of this event," says LRMH Assistant Director Thierry Zimmer.

THE LRMH RESEARCHERS work in the former stables of a 17th century chateau in Champs-sur-Marne, in the eastern suburbs of Paris, that once housed a horse research center. Here, they have analyzed samples from France's top monuments—the Eiffel Tower, the Arc de Triomphe—in the same rooms where some of the world's first artificial insemination experiments in horses occurred 120 years ago. The neighborhood is quiet, with a quaint brasserie and a shop offering €10 haircuts. But on a day in January, the lab is anything but sleepy. "It's an ambiance of speed!" says Zimmer, sporting a brown wool beret and a bushy mustache.

Véronique Vergès-Belmin, a geologist and head of LRMH's stone division, was sorting cathedral stones until 10 p.m. last night. This morning, she's the first to unlock the laboratory's ancient oak door.

She slips a hazmat suit over her dress clothes and slides on a respirator mask—necessary when dealing with samples contaminated with lead. In the lab's high-roofed storage hangar—once a garage for the chateau's carriages—she presents several dozen stones that fell from the cathedral's vaulted ceiling. Fallen stones hint at the condition of those still in place, which are largely inaccessible. The scientists can't risk adding their weight to the top of the vault, and debris falling near the holes in the ceiling makes it dangerous to inspect the structure from below. Many of the samples in the lab were retrieved by robots.

Heat can weaken limestone, and knowing the temperatures endured by these fallen stones can help engineers decide whether they can be reused. Vergès-Belmin has found that the stones' color can provide clues. At 300°C to 400°C, she says, iron crystals that help knit the limestone together begin to break down, turning the surface red. At 600°C, the color changes again as the crystals are transformed into a black iron oxide. By 800°C, the limestone loses all its iron oxides and becomes powdery lime. "It's an entire progressive process," she says, enunciating carefully through the muffle of the mask. "Any colored stones or parts should not be reused."

Color evaluation isn't an exact science, she says. Still, in lieu of mechanically testing each of the hundreds of thousands of stones that remain in the cathedral, color could be a useful guide to their strength.

Philippe Dillmann, an LRMH collaborator and a metal specialist with CNRS, the French national research agency, believes rust from the cathedral's iron structures can provide similar clues. At increasing temperatures, the microscopic structure of the rust changes. By investigating the cathedral's nuts and bolts—literally—as well as a "chaining" system of iron bars within and around its walls, Dillmann wants to create a heat map for the nearby stones. He says it's unknown whether these bars were used in construction and left in place or served as reinforcement. "We know they're in there, but they've never been studied," he says.

Water can also wreak havoc. Although the firefighters carefully avoided the stained glass windows, they had no choice but to drench the stone vault. The porous limestone gained up to one-third of its weight in water—and it's not set to lose it quickly. In the lab, LRMH researchers are monitoring a fallen stone, weighing it to track the drying process. When this article went to press, the stone was still losing weight.

Meanwhile, rainwater continues to fall on the roofless vault, and engineers can't install a temporary cover because of a mangled skeleton of scaffolding, set up in 2018 for long-term renovations. In January, workers began the 6-month process of removing the partly melted lattice. Because the cathedral walls support the scaffolding, it will have to be dismantled carefully, like a giant Jenga game, to prevent a collapse that could be "catastrophic," Magnien says.

Until the stones finish drying on their own, their changing weights will likely continue to have "nonnegligible" effects on the vault structure, according to Lise Leroux, a geologist in the LRMH stone division. Not only does the extra weight play with the precarious balance of forces, but when the water freezes in winter, individual stones expand or contract. "We'll start testing the mortar between the stones to see how well it's handling the strain," she says. "Now that I can get up there."

Weeks after the fire, engineers installed steel beams above the vault so technicians could rappel with ropes as they remove scaffolding and stabilize the structure. After earning a rappelling certification, Leroux last month inspected the top of the vault for the first time. She found that a plaster coating on top of the vault was still mostly intact, and had shielded many stones from fire and now rain. "It seems to have done its job," she says.

WHILE THE STONE SCIENTISTS are busy with mechanical forces, another team has concentrated on the whereabouts of the lead roof and spire. Along with grief, the fire stirred

Glass researcher Claudine Loisel found that baby wipes could sample for lead without damaging staining.

another emotion among Parisians: fear that vaporized lead had drifted into nearby neighborhoods. In fact, Aurélia Azéma, a metallurgist who leads LRMH's metal division, and other scientists have concluded that the fire maxed out well below lead's vaporization temperature of 1700°C. Most of the lead simply melted at 300°C, pouring into the gutters and dripping into stalactites that can still be seen hanging from the vaults.

In places, however, temperatures did exceed 600°C, at which point lead oxidizes into microscopic nodules—an aerosol. "It's like hair spray," Azéma says. A yellow cloud that billowed from the cathedral during the fire showed that at least some of the lead did get hot enough to become airborne.

Sophie Ayrault, a geochemist at the French Alternative Energies and Atomic Energy Commission, wants to know where that cloud ended up. Azéma collected samples of lead dust from two surfaces that had been cleaned just before the fire—the organ bench and a drape covering a statue—and Ayrault has analyzed the signature of isotopes in the lead, a fingerprint that distinguishes Notre Dame lead from other lead sources.

She hopes to compare the cathedral fingerprint with that of dust samples from throughout the city. Some nearby schools were decontaminated after samples showed worryingly high lead levels. But it's not clear whether the lead came from the Notre Dame fire or from some other source, such as lead paint, car batteries, and leaded gasoline. "Unfortunately the testing agencies destroyed the wipes," she says, so she can't test the schools' original samples. Her lab will soon start to test new samples taken from Parisian park surfaces and compare them with the Notre Dame signature.

Ayrault also suspects corrosion from sunlight and acid rain might have been releasing lead from Notre Dame's roof for centuries. With the flying buttresses designed to carry runoff quickly into the Seine River, Ayrault says Notre Dame may have been an ongoing source of water pollution. She's starting to look for lead in sediments collected downstream in Normandy. Again, she will try to assess how much of the lead came from Notre Dame versus other sources.

MUCH OF THE LEAD mobilized by the fire remains in Notre Dame. In June 2019, when Azéma and her colleagues brought their first samples from the cathedral back to the lab, tightly sealed in plastic bags, yellow lead dust appeared to be everywhere. She unrolls small organ pipes from layers of bubble wrap, and points her gloved finger at their holes. "Even down in here," she says.

Because of lead's toxicity, especially in children, France's national health agency imposes a legal limit of 0.1 micrograms per square centimeter on the surfaces of any building, including historical monuments. "My first sample was 70 times that," says Emmanuel Maurin, a wood scientist and head of LRMH's wood division, who tested surfaces like the oak confessional and choir seats.

The scientists are largely unconcerned about their personal exposures, and blood tests have shown no significant rise in their lead levels. "It's not like we're licking the walls," Zimmer says. Nevertheless, the national work inspection agency has enforced stringent safety requirements. People entering the cathedral must strip naked and put on disposable paper underwear and safety suits before passing through to contaminated areas, where they put on €900 protective masks with breathing assistance. After a maximum of 150 minutes' exposure, they peel off the paper clothes and hit the showers, scrubbing their bodies from head to toe. "We're taking five showers a day," Zimmer says, adding that getting through the showers can be "like the Métro at rush hour."

The Ministry of Culture has charged LRMH with finding a way to cleanse the cathedral of lead without harming it. Claudine Loisel, head of the LRMH glass division, has been testing decontamination techniques for the cathedral's 113 stained glass windows, which all survived. Already blackened and sticky with soot, dust, and residue arising from millions of tourists, worshippers, and votive candles, the windows lack the yellow-powder look. But with her binocular microscope, Loisel easily detects lead oxide nodules on three panels she brought to the laboratory. "The goal right now isn't to restore, but to decontaminate," says Loisel, decked from head to toe in protective equipment.

The national health agency uses commercial wet wipes to sample surfaces and test for lead. But the wipes contain small amounts of acid that could damage the window staining, so Loisel convinced the agency to accept a compromise: "chemical-free" baby wipes from the Monoprix grocery store chain.

Although this works for small-scale testing, the scientists don't want to clean the entire cathedral with baby wipes. For most smooth surfaces—glass, metal, waxed wood, and even paint—they've found that a shop vac and cotton pads, moistened with distilled water, safely remove the lead. Raw wood surfaces require fine sanding first, Maurin says.

The porous stones call for a different approach. One possibility is plastering them with a latex "silly putty" that can be pulled off along with the lead dust, Vergès-Belmin says. A similar method uses a clay-based compress that dries and contracts, creating lead-filled "chips" that can be collected and disposed of. A third idea is to use laser cleaning. The scientists will begin to test various

PHOTO: AP PHOTO/FRANCOIS MORI

methods in two of Notre Dame's chapels later this month. "We're most likely looking at a combination of techniques," she says.

AS THIS FIRST, "emergency" phase of scientific work advances, Notre Dame is slowly starting to open to "second phase" scientists—those interested in studying its history and architecture, now exposed by the fire and available to study without intruding crowds of tourists.

The Ministry of Culture and CNRS have created a dedicated science team of about 100 researchers from multiple institutions. By last month, about 10 CNRS researchers had gained some access to the cathedral for their work. The opportunities are generating palpable excitement among scientists and historians. "We're sorting all these thousands of fragments—some from our world, some from another and more ancient world—and it's like we're communicating with the Middle Ages," Dillmann says.

Yves Gallet, an art historian at Bordeaux Montaigne University, oversees a group that aims to study stones that are still in place, such as the encasements that cradle the four-story-diameter rose windows. Through detailed photographic analysis, the researchers want to understand how 13th century stonecutters designed and assembled the encasements, and the entire gothic masterpiece. Their analysis of mortar throughout the cathedral could confirm what historians believe about the order of the building's construction and repairs. "The mortar can tell us a lot about which stones were placed at the same time and what kinds of forces were anticipated in those areas," he says.

Before going that high up, Gallet hopes to use a ground-penetrating radar in a first study of what lies beneath the cathedral's ground floor. By interpreting the echoes of radar waves, Gallet and his colleagues could identify stonework that predates Notre Dame. He wonders whether he'll find remnants of the earlier churches that some scholars believe were built at the site. "We actually have no idea what's under there," he says. Ongoing cathedral activity ruled out such a study before.

Meanwhile, Leroux is eager to trace the origin of the vault stones. Many are said to have been quarried in Montparnasse, a nearby Paris district, but she thinks their origins are more diverse. "See this arrangement of plankton fossils mixed with clay and quartz?" she asks, a fallen stone in hand. "That's not from Montparnasse!" She turns to her archive drawers of 6000 samples and pulls out a stony sliver labeled "Pont d'Iena"—the Parisian bridge next to the Eiffel Tower. "This is a perfect match," she announces. "I found it." She says the bridge and vault stones both hail from a quarry in the French Vexin, a forest an hour northwest of Paris.

The charred remnants of attic timbers have stories of their own to tell, says Alexa Dufraisse, a CNRS researcher heading the wood group. Variations in thickness, density, and chemical composition of growth rings reveal climatic conditions year by year. "Wood registers absolutely everything while it's growing," she says. Notre Dame's oak beams grew in the 12th and 13th centuries, a warm period known as the Medieval Climate Optimum. By connecting the growth ring record with what's known about economic conditions at the time, researchers hope to see how climate variations affected medieval society, she says.

This gold angel once sat atop Notre Dame. It survived a fire and a fall. Researchers discovered the signature of its unknown sculptor.

PHOTO: AP PHOTO/FRANCOIS MORI

The shape of the beams also intrigues the wood team. Long and narrow, they clearly grew in a dense, competitive environment, Dufraisse says. That supports the "silviculture" hypothesis, the idea that the trees were purposefully reserved or farmed for the cathedral. Their age at cutting—about 100 years old—would suggest people were planning Notre Dame several generations before construction began.

The location of that forest is another mystery Dufraisse's team is tackling, using the beams' chemical composition. The Paris area is likely, but boats might have shipped wood along the Seine from farther away. Soils contain levels of strontium and neodymium isotopes that vary from region to region, but stay constant over the centuries—especially at the depths tapped by the roots of oak trees. So her group is seeking to match the wood's isotopic makeup to that of soil in likely locations. "These questions will also be pertinent if we're looking at meeting the requirement of reconstruction that's identical to the original," she says.

As for Maurin, he's investigating the builders' marks on the roof support beams. Applied by men shaping the beams on the ground, they were meant as instructions for the assembly team working more than 30 meters above them. "It was kind of the IKEA of the Middle Ages," he says.

BEYOND THE PHYSICAL damage left by the fire is the emotional trauma suffered by thousands of Parisians and others, and CNRS researchers are also investigating this hidden aftermath. Sylvie Sagnes, a CNRS ethnologist with the Interdisciplinary Institute of Contemporary Anthropology in Paris, is part of a group that will interview tourists, locals, guides, journalists, donors, and church members to analyze the fire's emotional effect. She says people can display a powerful attachment to monuments, parks, and historical sites. When people mobilize to protect heritage, she says, it's a democratic expression—something French anthropologists studied 30 years ago during a public outcry against planned renovations of a basilica in Toulouse. In the case of Notre Dame, strong feelings are intensifying controversies around its restoration, such as whether to rebuild it exactly as it was. "Notre Dame isn't just any monument," she says. "After the fire, people remain emotionally implicated."

Valérie Tesnier, a café owner down the street from Notre Dame, says she's noticed a change in the behavior of tourists. They now solemnly watch the restoration effort before moving along—usually without stopping for food. "They don't want to stay and prolong their grief," says Tesnier, who has just sold her once-thriving business.

Across centuries marked by war and disease, Notre Dame has witnessed cycles of decline and renewal before. The LRMH scientists hope that when the vaults and buttresses are again dry and sound, the lead accounted for, and the great cathedral's history and resilience understood more deeply than before, grief and loss will once again turn to joy and gratitude.

"Certainly this is a difficult period emotionally, but there's an extraordinary unity of people coming together to not only save this monument, but to learn from it," Magnien says. "Notre Dame will be restored! Its artwork, stone, and stained glass will be cleaned; it will be more luminous and beautiful than before."

"Notre Dame will come out of this experience enriched," she says. "And so will we." ■

Christa Lesté-Lasserre is a journalist in Paris.

Science

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