The Notre-Dame Translation Project

XI. The Environment & Notre-Dame

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2021

Notre-Dame's Statues of the Kings of Judah: Witnesses of the Air Pollution in Paris from the Middle Ages to the French Revolution of 1789

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Translated & Edited by Lindsay S. Cook

The statues of the Kings of Judah, ancestors of the Virgin Mary and Christ, adorned the gallery of the western frontispiece of Notre-Dame, above the three great portals, from the 13th century until the French Revolution. In 1793, they were defaced, decapitated, and thrown to the ground by revolutionaries, who presumably elided them with representations of the kings of France. The debris was removed to an unknown location in 1796. In the 19th century, Viollet-le-Duc had the copies made that we now see on the façade of the cathedral (Delmonte et al., 2001).

In 1977, 21 of the 28 original heads were discovered fortuitously during an underground construction project on the rue de la Chaussée d'Antin, and they were transported to the Musée de Cluny in Paris, where they have been on display since their restoration. Macroscopic analysis revealed the presence of gray crusts on the statues' surfaces, but not on the place where they were cut at the neck: these gray encrustations thus formed before the heads were buried—that is, during their exposure to the atmosphere of Paris between the 13th and the end of the 18th century.

Microscopic analysis of samples performed on the gray crusts on the surface of the statues revealed the presence of abundant debris of wood cemented by a mineral coating that is mostly calcic ($CaCO_3$) and not very gypseous ($CaSO_4$, $2H_2O$), reflecting the preponderance of carbon dioxide (CO_2) in the air at the time in Paris, due to the combustion of wood. The absence of fly ash characteristic of the burning of coal or petroleum products confirmed the pre-industrial age of the gray crusts.

The massive and exclusive use of wood in Paris—a major source of the carbon particles found in the gray crusts—before the introduction of coal in the early 19th century, is attested not only by the aforementioned debris found on the heads of the statues of the Kings of Judah from the Notre-Dame façade, but also in literature (Digby, 1658; Le Bègue de Presle, 1763) and paintings of the same period (Demachy, 1770). The statues of the western frontispiece of Notre-Dame are thus a precious and unique material index for the air quality in Paris from the Middle Ages to the Revolutionary period, even though the amount of pollution in the air in Paris was not measured at the time.

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Will the Stone and Glass of the Restored Notre-Dame Resist Air Pollution and Climate Change?

Written by Roger-Alexandre Lefèvre (source)
Translated & Edited by Lindsay S. Cook

The two principal materials that comprise the building envelope of Notre-Dame (beyond the roof and framework, which we do not know at this point what they will be made of after restoration/repair/reconstruction) are *Parisian limestone* and *glass of the historic stained-glass windows*. Like all cultural heritage materials, they have experienced extreme conditions, an unfortunate example of which is the 2019 fire, and gradual events connected to air pollution and the climate, current changes to which are worrisome. Situated in the heart of Paris, the cathedral is exposed to air pollution, rain, and air temperature and humidity fluctuations. Pollution darkens the stone and glass by depositing particles on parts sheltered from the rain; rain erodes the cathedral by dissolving the stone and the chemical leaching of the stained glass; finally, the air temperature and humidity are in direct relation to contemporary climate change. What effects did these four major factors have in the past, and what effects are they projected to have in the decades to come? The *pollution of the air in Paris since 1500* was reconstructed thanks to historical data (wood and coal burning stoves in Paris, literary accounts, works of art), as well as quantitative measurements taken by the Laboratoire d'Hygiène de la Ville de Paris and the air-quality monitoring network AIRPARIF. Air pollution was projected through 2100 by means of the emissions model GAINS (fig. 1). Thus we see that the concentration of SO_2, NO_2, and PM10 in the Parisian air rose gradually until the beginning of the 19th century, and then steeply since the introduction of coal and petroleum-based products, before declining in the second half of the 20th century with the abandonment of coal, fuel desulfurization, and catalytic filtration of vehicle emissions. This downward trend will likely continue until the end of the 21st century, if we are to believe the predictive models.

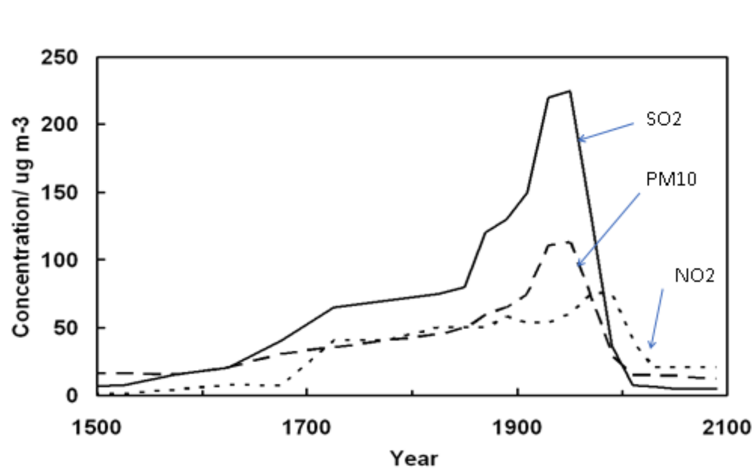

Fig. 1 Concentrations of SO_2, PM10, and NO_2 in the Paris air from 1500 to 2100 (Ionescu et al., 2012)

The darkening or "soiling" of the limestone (Fig. 2) and its erosion (Fig. 3), established and projected on the basis of the same historical data, measurements of atmospheric pollution, the emissions model GAINS, and the climactic model Aladin-Climat of Météo-France (the French national meteorological service), in the scenarios RCP 2.6 and 8.5 of the 5th report of the GIEC (2014), all of which were introduced into the dose-rose function (Lipfert 1989 and ICP Materials in Tidblad, 2010), follows a trajectory parallel to that of the atmospheric pollutants (Fig. 1).

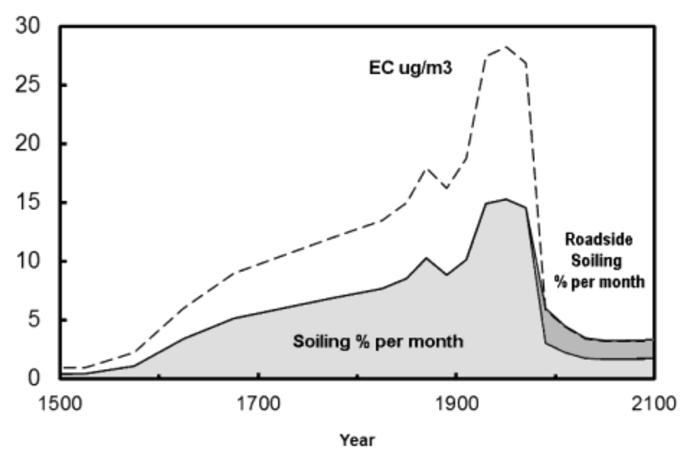

Fig. 2 Soiling of façades in Paris from 1500 to 2100 (Lefèvre et al., 2015)

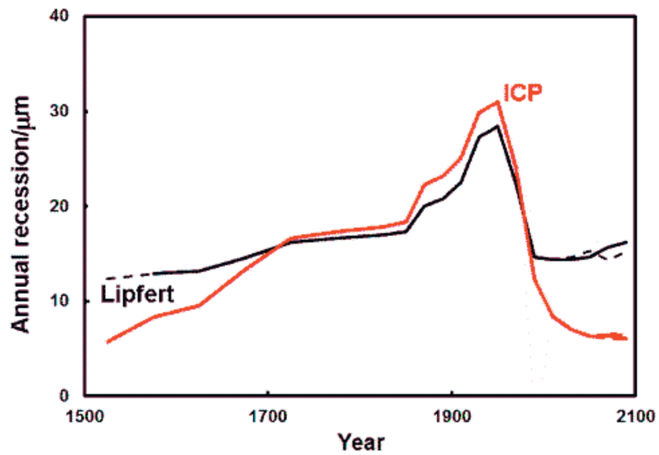

Fig. 3 Recession rate of new limestone (Lefèvre et al., 2015)

As for the chemical leaching of the stained-glass windows caused by atmospheric humidity (outside of direct rain, although that is even more of a factor), which extracts calcium and potassium from their surface, enriching it in silica, it follows the same past and future developments.

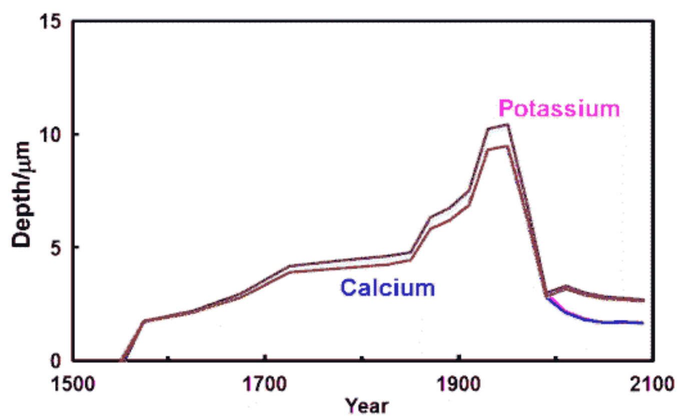

Fig. 4 Depth of chemical leaching of K and Ca under the surface of a new stained-glass window, of the chemical composition Si-Ca-K, protected from the rain, in Paris, from 1500 to 2100 (Ionescu et al., 2012)

In conclusion, we can easily understand, in view of the results summarized above, that air pollution in Paris and the impact of climate change do not pose a particular threat to the mineral building envelope (stone and glass) of Notre-Dame. However, this relatively optimistic prediction will only come to fruition if the municipality's efforts to reduce air pollution in the capital continue, the cathedral is subject to effective preventative maintenance (regular cleaning, protective glazing), and the global average surface temperature rise is kept under 2ºC or 1.5ºC.

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Limestones: Density, Porosity, and Weaknesses: Protective Elements (Biofilm)

Written by Bruno Phalip (source)
Translated & Edited by Lindsay S. Cook

Church of St. Mary of Carmel, Famagusta, Cyprus, late-13th century/early-14th century

Limestones remain in a stable state (in terms of their temperature and water content) as long as they are not extracted. In the quarry, extraction represents a first trauma, followed by others related to both cutting and sculpting. At the same time, the material begins to lose the "quarry water" it contained prior to extraction and enters a drying phase. The finer the stone is cut, to correspond to the intended shape of the sculptures, the more the limestone is weakened: it contracts during dry periods and expands during humid ones. The list of alterations the stone undergoes is long. In the case of limestones, the stone tends to form a protective layer made up of surface deposits, left during the initial phase, when the calcium-rich "quarry water" evaporates from the stone after it is cut, sculpted, and installed. This layer provides a thermal and hydric shield, which may be supplemented by another one, called biofilm. Between nine and fifteen months after an exterior stone is laid, bacteria and cyanobacteria colonize its cut surfaces. Four or five years later, depending on the exterior environment, lichens and mosses acclimate to and populate the cladding that is exposed to humidity. This is a kind of "lesser" vegetation (without a root system), which protects against large fluctuations in temperature and meteoric water: ice, hail, rain, snow, temperature differences between night and day, summer and winter, etc. Long cleaned to make them disappear (by bleaching the material), the protective layer and biofilm are still rarely respected and recognized for their qualities: protection and porosity. It only affects the visual appearance, as with acid attacks by means of anchoring by rhizines or mycelia. Nevertheless, each cleaning or treatment (using biocide/ phytosanitary or waterproofing products), degrades the surface of the stones (by a few microns per cleaning) and alters the most fragile parts. Covered stones can go eight to ten centuries without any major damage; from restorations and cleaning, the changes to the stone are exponential: pollution (nitrates, phosphates, exhaust and heating gas), especially in urban environments, that degrade the protective layer to form crusts, dust, chemical and physical wear by dissolution and fracturing (fragmentation, exfoliation, cavitation...).

The cathedral Notre-Dame of Paris comprises several types of limestone quarried and cut or sculpted not only in the 12th and 13th century, but also in the 19th century (the combination of medieval stones with new stones is often a factor in accelerating their alteration). The impact of the fire caused a new trauma by the reddening, thermal shock, and potential conversion into quicklime of the surface of the limestone blocks.

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Using Isotopes of Lead to Determine the Environmental Impact of the Notre-Dame Fire

Written by Sophie Ayrault, Edwige Pons-Branchu, and Laurence Lestel
(source)
Translated & Edited by Lindsay S. Cook

Paris, Notre-Dame, lead roof and ridge crest (photo: Arnaud Timbert)

On the night of April 15-16, 2019, a fire destroyed most of the roof of Notre-Dame of Paris. The spire, covered in sheets of lead, was the first to be claimed by the flames and fall into the nave. The fire then claimed the roof, whose covering was also made of lead (around 200 tons of lead in total, according to the most recent estimates). The temperatures reached, between 600 and 900°C—if not higher, that remains to be seen—led to the aerosolization (the production of fairly small particles, aerosols, to be carried through the air) of some of the lead in the form of lead oxide, responsible for the yellowish color of the smoke. Dust from these plumes of smoke fell to the ground in and around the cathedral. Another portion of the lead can still be found in the structure in the form of "drops" or "puddles," which fell on the ground or on the tops of the vaults, and fragments of lead sheets.

The principle of the isotopic signature

Isotopes are the different atoms of a single chemical element. They all have the same chemical properties, but differ slightly in mass. The analysis of a sample by mass spectrometry allows us to identify these isotopes and to measure the concentration of each one. These characteristics form the isotopic signature of the chemical element in the sample. Lead has 38 known isotopes. Four of them, ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb, are stable (non-radioactive: they do not change over time) and constitute natural lead. Their relative abundance in nature is 1.5%, 24.1%, 22.1%, and 52.3%, respectively. To explain the variation of the proportions of the four isotopes, we must remember that they result from three chains of radioactive decay: ^{208}Pb (majority) is the (stable) final decay product of thorium 232; ^{206}Pb is that of uranium 238, and ^{207}Pb is that of uranium 235. The relative quantities of different stable isotopes of lead change, therefore, over time, imprinting the ore with isotopic ratios characteristic of the mine. These ratios, also known as "signatures," are conserved from the mine from which the lead was extracted to the finished material, regardless of the number of times it is subject to casting or recasting. Consequently, the isotopic signature may be used to determine the date when the lead was first used, enabling an understanding of commercial routes for lead throughout history (Alfonso et al., 2001; Ayrault et al., 2012; Monna et al., 2000). These routes were complex already in the Roman period, with lead being used as a decorative element or as an ingredient in bronze (Nriagu, 1983). The analysis of the isotopes of lead of the dust produced by the fire will allow scholars to establish the signature of this incident, trace it in contaminations outside of the building, and identify where in the building the various elements that fell on the ground or are still present in the structure originated.

Taking soil, atmospheric particle, and river sediment samples

Tracing the history of lead pollution

Researchers from the LSCE lab (Laboratoire des Sciences du Climat et de l'Environnement) and the METIS lab (Milieux environnementaux, transferts et interactions dans les hydrosystèmes et les sols) have been studying the cycle of lead in the Seine River basin for more than a decade. Notably, they have characterized various signatures in Paris and its environs. A large quantity of lead is found in the urban infrastructure (pipelines, sealing elements of roofs, balconies, interior and exterior paint…). During Haussmann's mid-19th-century renovation of Paris, much of the lead used beyond that which was recycled was imported from the Rio Tinto mine in Spain.

It has also been shown that the lead of fuel additives used in the 20th century, which has a specific signature, were a major source of contamination, even though the quantity of lead used for this purpose was relatively small (5% max) (PIREN-Seine; Ayrault et al., 2012).

Over the centuries and through recycling, the various sources of lead have been amalgamated, forming what we have called "urban lead" (Le Pape et al., 2013), the signature of which is found everywhere (Ayrault et al., 2014). Signatures typical of anthropogenic lead have been found for the past 300 years, as shown by the study of underground limestone warehouses (Pons-Branchu et al., 2015). We hope to collect data covering a longer period in hopes of identifying the various historical intakes of lead in Paris over several centuries, including the renovation of the 19th century, or even the construction of the edifice (projet HUNIWERS).

Analyzing the lead of Notre-Dame: issues and perspectives

The lead comprising (or once comprising) the slopes of the Notre-Dame roof, which partially melted and was "aerosolized" during the fire, has various origins, because the elements of the roof were largely put in place during three distinct periods: during construction in the 12th and 13th century, during the retrofit commissioned by the cardinal of Noailles at the beginning of the 18th century, and during Viollet-le-Duc's restoration in the 19th century. The mines exploited varied over time: lead could be extracted in France (from the mines in Melle, for example, during the High Middle Ages). Later additions generally came from Spain, which furnished France with around 1,500 tons of ore and 15,000 tons of lead metal, on average, annually from 1820-1848.

During the successive renovations, it is very likely that old medieval sheets of lead were reused, with a brazier melting the lead easily. On the basis of signatures of isotopic ratios, it could be possible to identify the different periods of fabrication of the lead sheets and calculate the proportion of lead reused, especially in the elements dating to the 19th century that cover the roof and spire. A fortiori, we should be able to distinguish between lead from the Middle Ages and lead from the 19th century.

The signature of this lead, or of these leads, has never been identified, unlike that of the rustproof paint of the Eiffel Tower, whose contribution to the contamination of dust nearby has been measured (Nageotte et al, 1998). We must now identify the source "NDdP" contributing to the flow of lead in Paris. This work should not only address the present (based on the analysis of urban runoff, sediments, atmospheric particles, etc.), but also the more distant past, all the way back to the construction of Notre-Dame, if natural archives that have recorded this information can be found. The fire served as a call to action. In order to do so, it would also be necessary to be able to identify lead objects made by the same workshop and around the same time as Notre-Dame, for buildings that haven't burned or surviving objects from Notre-Dame, in order to analyze them. All of this will require fieldwork.

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