The Restoration of Medieval Stained Glass*

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The victim of its own composition and of modern air pollution, Europe's most radiant art is now threatened with destruction. The efforts at preservation depend on knowledge of the glass.

Light has long served religion as a symbol. It has signified creation (" Let there be light" was the first command of the Creator) as well as salvation (John the Evangelist saw the Heavenly Jerusalem illuminated as if made " of jasper" and its walls " like clear glass") The earthly reflections of such visions, achieved throughout the Middle Ages by means of light, were the period's most brilliant works of art: the stained glass windows of Romanesque and Gothic chapels, churches, minsters and cathedrals. For almost a millennium, in the case of the earliest stained-glass windows, the glass escaped major damage. Even the catastrophe of World War II inflicted harm that was within bearable limits. In fact, stained glass all over Europe was removed to safety. Today, however, its total destruction is threatened, not by war but by air pollution. If stained glass windows are kept in their present state of preservation, their total ruin can be predicted within our generation.

A few examples will illustrate the threat. The stained - glass windows of Cologne Cathedral, in the immediate vicinity of the city's main railway station, have been unusually vulnerable. They were endangered by exterior weathering and air pollution as early as the mid19th century. Seen from outside the building, the windows now look like sheets of chalky plaster. Continuous etching by air pollutants has corroded the exterior surface of the glass, reducing its thickness year by year and giving the decomposed surface a so-called weathering crust. The process of destruction starts anew as each rain washes the crust away. Meanwhile the colored glass itself breaks into tiny particles. The particles fall out of each panel: thus the window disintegrates.

In England stained-glass windows are exposed to heavy smog. Canterbury Cathedral displays the results. The cathedral includes the Trinity chapel and its ambulatory, or processional aisle, which incorporates the chapel called the Corona, constructed between 1174 and 1220. In both chapels some of the stained glass has been attacked. Pits have formed, which have now perforated the panels, leaving them quite porous, so that acid rain can reach the inner surface of the glass and eat into the paintwork there.

France is the classic repository of stained glass. A single cathedral, the one in Chartres, is decorated with more than 2,000 square meters of stained glass from the 12th and 13th centuries, the period when the art reached its peak in France. As recently as 20 years ago one could marvel at the glass, and in particular at the richness achieved in the predominantly blue panes of the Romanesque and early Gothic periods: the "blue miracle" of Chartres. Today the contrast is shocking. The blue has not lost all its intensity; indeed, the chemical composition of the blue glass has made it relatively resistant to weathering. (In German speaking countries the green glass has proved least susceptible to weathering.) The panes of other colors, however, have corroded and turned a mangy brown, rendering the stained-glass images barely recognisable.

Medieval stained-glass windows are constructions of extreme fragility. Each consists of numerous pieces of colored glass of varying chemical composition held together in a firm but elastic network of cames, or thin lead strips with grooves to hold the glass. The cames follow the lines of the composition, producing a unified, mosaic like image. In most cases the glass was colored with metal oxides, which were put into the molten mass at the time the glass was manufactured. The exception was flashed glass, in which a thin film of color (usually red) was fused on to a clear base glass. Detailed effects could then be achieved by grinding away parts of the colored film. In the early 14th century silver stain was introduced. It consisted of silver nitrate bound in clay or ocher. The stain was painted on to the outer surface of the glass; then the glass was fired, that is, given its final heating. The result was a color ranging from light lemon yellow to deep orange. Finally, in the middle of the 15th century, sanguine was introduced. Sanguine is a pigment containing iron sulfite. Applied to the outer suface of the glass, it takes on a rose to red-brown tint on firing.

The decoration of the colored glass was achieved primarily by means of paintwork known as grisaille, applied to the surface of the glass. As a rule the painting was executed in black or a dark neutral tone. The paint itself was a mixture of copper oxide or iron oxide (which lent the mixture a black, brown or grey-green color), pulverized glass (which allowed the paint to fuse with the surface of the glass when the pane was fired) and a binding agent such as a mixture of wine and gum arabic, from the acacia tree. The paint was applied as opaque lines or as translucent matts or washes. Dark shading could be reinforced by painting the outer as well as inner surface of the glass. The washes could then be lightened with a needle or a quill. Anyone admiring medieval stained glass at close range for the first time cannot help but be struck by the precision of detail and the subtlety of the means employed in works of art intended to be viewed from a great distance. The final step in the preparation of the pieces of glass was their firing at some 600 degrees Celsius, the temperature at which the surface of the glass would soften and the paint on it would fuse.

From the moment they were in place the panels were in danger. The immediate threats included not only the effects of hail, windstorms and extreme fluctuations of air temperature but also wanton destruction, such as the hurling of stones by vandals. In the Middle Ages religious institutions routinely contracted with glaziers for the maintenance of their glass. The caretaking consisted in cleaning (washing with water, carbonate of soda and a sponge), the repair of cames and the replacement of shattered panels.

Apart From these external threats the glass itself was susceptible to a process of decomposition. Medieval glass was made from local raw materials, usually a mixture of one part sand and two parts ash from beechwood or fern. The mixture had the advantage of being easy to melt. The glass, however, had the disadvantage of being soft, a property that made it susceptible to weathering. The process of decomposition set in as soon as the glass was installed in the form of window panels. Water arriving at the surface of the panel as rain or dew would hydrate the glass material. In particular, hydrogen ions from the water would take the place of alkali ions in the glass: chiefly potassiun and calcium ions. Hydroxyl (OH) ions from the water would then attack the silica (SiO_2) in the glass, turning it from a polymer into a silica gel: an amorphous material consisting of short silica fragments. Eventually, with the alkalis leached out, only silica would remain. The silica layer can be particularly damaging to the appearance of stained glass. The layer can become iridescent, making the panels increasingly opaque.

Since the early 19th century the external threats and the internal ones have been augmented by the hazards associated with industrialization. The chief of these is sulfur dioxide, which is given off into the atmosphere not only by manufacturing processes but also by the burning of coal and oil. Sulfur dioxide combines with humidity to create sulfuric acid, which increases the availability of hydrogen ions. In addition it makes sulfate groups available to react with alkalis such as calcium. The resulting light, chalky layers of sulfates form a weathering crust that can be several millimeters thick. The crust is highly hygroscopic: it absorbs water like a sponge, thus accelerating the destruction of the glass Chemical analyses prove that the destruction attributable to sulfur dioxide goes back no more than 10 or 20 years. The rapidity of the destruction can be documented by comparing panels from the same window when some are still in place and others have been transferred to a museum.

The durability of a particular piece of medieval glass depends on a combination of circumstances: the chemical composition of the glass, the metal oxide coloring agent employed, the temperature at which the glass was made and the length of time it was molten during the manufacture. The temperature is crucial. Studies have now established that the melting point of medieval glass ranges from 300 to 900 degrees C. Glass from the Romanesque period (roughly from 500 to 1150) has a fairly high melting point; in glass from the Gothic period (roughly from

1150 to 1550) the melting point is lower. (Glass made still later, in the Renaissance, has the highest melting point.) In general, glass with a high melting point is the most resistant to weathering. The temperature required to manufacture it tends to ensure that its composition is homogeneous and gives it a well-formed. fire-polished surface, which in turn denies footholds to corrosion.

This is not to say that a high melting point is an unmitigated advantage. The glass particles in the paint employed for linework and halftones on the surface of stained-glass panes melt at about 600 degrees C. If the melting point of the pane is substantially greater, the fusion between the two is poor. The result in the course of time is particularly obvious in Renaissance glass. The glass itself is barely corroded, whereas the paint on it is quite poorly preserved. Undoubtedly medieval glass painters were aware of the imperfect fusion between their paint and high-melting-point glass. Sometimes, however, they seem to have wished the problem away. In *Diversarium artium schedula*, a manuscript written between 1110 and 1140, the German monk Theophilus instructed glassmakers removing glass from the firing kiln to "see if you can scrape off the pigment with your fingernail; if not, it is sufficient, but if you can, put it back again."

Certain aspects of the medieval firing process are of some importance for conservators attempting to save the glass today. Pieces of glass ready for firing were often stacked in layers in the kiln; thus the paint evaporating slightly from the surface of a piece in the course of high-temperature firing produced a faint metallic imprint on the piece stacked above or below. The imprint was invisible at the time. Nevertheless, it reduced the susceptibility to corrosion. The Coronation of the Virgin, depicted in the Martyrs Window at Freiburg Cathedral, furnishes an instance. Christ, who is seated next to Mary, wears a crown, which appears faintly, in an imprinted mirror image, on the back of the Virgin's head. The imprinted area is intact. uncorroded glass; the rest is covered by a powdery weathering crust.

Although the danger confronting stained glass today is acute, the problem of its deterioration has a long history. At the time of the Reformation, which rejected sacred ornamentation, the art of stained glass came to a standstill. Some stained-glass panels simply fell into ruin. (As early as 1639 one observer, Adam Gering, was complaining about Freiburg cathedral: "How terribly the precious windows are already damaged!") Some panels lost so much of their translucency that sections of clear glass were fitted into their midst in order to lighten the interior of the building. The Baroque and the Enlightenment, with their lack of interest in medieval relics, only heightened the neglect. ("Because these painted windows turn everything very dark, heavy and dull, they are disposed of everywhere," a priest of Freiburg Cathedral noted in 1787.).

In the early 19th century interest in stained glass revived. Unfortunately a misguided ambition to surpass the old masters triggered a second wave of destruction. Throughout Europe new generations of glass painters occupied themselves with what they considered "restoration." Damaged panes were replaced by new ones. Damaged grisaille was repainted and refired. In many cases the original panels disappeared, doubtless hoarded by collectors. At the end of the century practices changed. Enthusiasm waned and money became scarce. Hence damaged originals were no longer replaced by copies. Instead original panels were cut up and the pieces were inserted in damaged panels as stopgaps.

1 Augsburg, Cathedral, Prophet Hoseas, half-cleaned

2,3 Damage to stained glass from the Middle Ages takes different forms depending on the composition of the glass and the conditions to which it has been exposed. The panel on the left, depicting Adam, is from the great west window of Canterbury Cathedral, for which it was made in about A. D. 1180. Smog and the permanent high humidity have pitted the glass, which in places is perforated like a sieve. The damage is plain on the flesh-tone glass representing Adam's head and body. The panel on the right, depicting three warriors, is from the Church of St. Patrokoli in Soest, Germany; it was made before 1166. Over the centuries the surface of the glass has been oxidized. The places with painted linework and halftone were protected for a while. When the paint fell away, however, a negative image remained. The damage is particularly evident on the faces. The green colored panes have resisted damage the best.

The early 20th century brought a number of experimental treatments of stained-glass panels. In the first decade of the century, for example, two panels from the Church of St. Sebaldus in Nuremberg were thinly coated with a low-melting-point overglazing (in particular an enamel) and refired, in order to reattach the grisaille. The damage inflicted by this process was severe. Nevertheless, the treatment was applied to more than 200 stained-glass windows until 1939.

How, then, can medieval stained glass be restored and preserved? The example of the Church of St. Lorenz in Nuremberg demonstrates that in each individual case restoration poses particular problems. There the corrosion caused by air pollution was already under way in late medieval times: adjacent to the church the burghers of Nuremberg treated hops with sulfur. The damage to the glass was apparently not minor. At the end of the 15th century the Council of Nuremberg appointed the famous workshop of Veit Hirsvogel the Elder as the official glazier of the city. Four centuries later the windows of the church were subjected to "restoration". Between 1829 and 1840 the glass painter Johann Jakob Kellner and his four sons removed damaged panes from five choir windows and replaced them with copies or with entirely new creations. The original glass was reduced by 40 percent. The whereabouts of the originals are largely unknown today. Some pieces emerged on the art market and others in the German National Museum in Nuremberg. Examination of the few available specimens shows that they were not damaged sufficiently to have warranted their removal.

Twentieth-century pollution intensified the deterioration of the St. Lorenz stained glass. Joseph Schmitz, a Nuremberg architect and the son of a glass painter, began to examine methods of conservation. In 1917, after many years of experimentation, test panels were chosen from the Church of St. Sebaldus in Nuremberg. The panels were disassembled; then the pieces were coated with a vitreous dust, which, on refiring, produced an overglazing. Two decades later the Bavarian State Bureau for Conservation decided to employ the method on a larger scale at the Church of St. Lorenz. The outer surface of many types of glass in the St. Lorenz panels was heavily corroded; a thick weathering crust made the panels virtually opaque. The grisaille rested loosely on the inner surface of the glass and fell off in flakes.

The conservators removed the crust by abrasion and applied a low-melting-point overglazing enamel. The inner surface also was cleaned and overglazed, after the loosened grisaille had been carefully pressed down with blotting paper. Efforts began with the Konhofer Window, a work dating to 1477 and created in the workshop of Michael Wohlgemuth, the teacher of Albrecht Dürer. It soon became apparent that the low temperature chosen for the refiring failed to produce a satisfactory refusion of paint to glass. The temperature was increased, where upon the grisaille fused. In addition, however, a greenish discoloration developed and the paint blurred. At the same time the pieces of glass having a high content of iron and manganese, among them the flesh-tone pieces, turned dark brown. The treatment continued nonetheless, until finally stopped by World War II.

The renewal of conservation efforts in 1968 in my studio at the Institute for Stained Glass Research and Restoration in Nuremberg revealed the true extent of the damage. The refiring and subsequent cooling of the St. Lorenz glass had subjected it to thermal strain, so that it was cracked and in places broken. For its part the overglaze had bubbled, and it was corroding faster than the original glass. The overglaze could be removed with a fiberglass brush, but the exposed paint was unprotected once again.

During the 1950's the church itself was reconstructed. In the course of the effort Richard Jakobi, the former director of the Doerner Institute, undertook to safeguard the church's stained glass. In particular he attempted to sandwich each piece of glass between layers of glass, with a plastic foil separating the original glass from its inner and outer covers. The process had first been tried, with disappointing results, on a panel from Naumburg Cathedral in 1939. Again the individual panes were removed from their network of cames. Splintered pieces in each pane were glued along their edges and reassembled. (Most of the panes were in splinters, each a few millimeters long.) Then a clay-and-plaster mold was made of each side of the pane. Two cover glasses about .8 millimeter thick were cut to the size of the pane, then placed in the molds and settled at a temperature of between 700 and 800 degrees, so that they now had the contours of the surfaces of the original. Finally the original was sandwiched between its new cover glasses. The glass layers were glued together, at a temperature of about 200 degrees, with plexigum foil, a soft acrylic.

The treatment secured the stained glass against air pollution, humidity and even storms and hail. Yet the approach has four serious disadvantages, which have made it obsolete. First, the application of a cover glass and a plastic foil to the inner surface of stained glass produces a wet-glass effect: a tendency to reflect light, which lessens the visibility of areas painted in subtle halftones. Second, the making of a mold without first reattaching the painted linework is unfortunate: a substantial part of the loose paint inevitably is lost. The subsequent lamination of the panel also takes a toll on the paint. Third, the heating of the sandwich to a temperature of 200 degrees may ultimately damage the glass. It is possible, for example, that internal stress induced by the heating will lead to disintegration. Finally, the use of untested new plastic products in restoration projects is potentially dangerous. In the Church of St. Lorenz damage in fact has occurred. Under the influence of the sun's ultraviolet radiation the plastic employed to join broken edges has turned dark brown.

In 1982 my colleagues and I undid the lamination. Our primary task, during a quarter century of restoration of the stained glass at the Church of St. Lorenz under my direction, has been to use carefully aimed prophylactic measures to create conditions approximating those of a museum.

The first stage in our work is the cleaning of the glass. The purpose of the cleaning is not the improvement of the translucency of the glass. It is the removal of a dangerous source of corrosion, the weathering crust, which attracts moisture. In addition the cleaning exposes what is left of the original paintwork, so that its state of preservation can be accurately judged.

Loose parts of the painted trace lines and halftones are reattached to the glass; otherwise they would be lost. The reattachment is done with a nonyellowing acrylic, a substance that can always be redissolved by future conservators. The next stage is restoration. Here no procedure is guaranteed, reliable and universal; each specimen of stained glass requires individual treatment.

Still, the glass can be protected by two measures. The first is double glazing. A protective pane of glass, not attached to the stained-glass panel, is installed. Second, the temperature and humidity between the stained glass and the protective panel can be controlled, as they would be in a museum. The idea is to superpose an air cushion between the atmosphere and the exterior of the glass. After all, the chief factor that triggers the corrosion of stained glass is humidity. Without humidity even the highest concentration of sulfur dioxide would do no harm.

The oldest double glazing known was installed in England's York Minster in 1861. The intent was simply to improve the building's insulation against the cold. The serendipitous protection of stained-glass windows against exposure to the weather was noted with gratitude later. The protection, however, was unaesthetic. It came in the form of large, greenish sheets of machine-rolled, textured glass; placed between the stained glass and the sky, the new glass not only interfered with the look of the building from outside but also diminished the luminosity of the stained glass viewed from within. Moreover, the sheets were firmly mortared into position, and the tension resulting from their expansion had broken all but one of them after some 45 years.

A second experiment with double glazing came in 1897. Its subject was the Romanesque stained-glass cycle in the small church of Lindenau, now in the German Democratic Republic. Two panels of the cycle have been in the collection of the German National Museum for almost 80 years. Their state of preservation resembles that of the glass still in place in the church. The safeguarding afforded by double glazing evidently corresponds to museum conditions.

Although double glazing protects the exterior of the window, there remains a critical threat to the inner surface of the glass, a threat that arises from the heating of medieval churches. As a rule the churches were not designed to be heated: they have no insulation in their floor, walls, ceilings and windows. The beneficial result is that the relative humidity inside the building has fluctuated little over the centuries. The thick walls have served as a buffer, absorbing moisture or releasing it. Heating, on the other hand, produces a temperature difference between the interior and the exterior of the church, particularly when the heat is turned up quickly in preparation for a service. The humidity in the air then condenses on poorly insulated surfaces, notably the inside of the windows. The humidity traps air pollutants, and so the destruction begins. Grisaille and the glass itself begin to decompose. The painted surface, which for a time had protected the underlying glass, remains discernible in the form of a negative image.

The type of deterioration that produces a negative image is often accompanied by an entirely different process of corrosion, one whose mechanism has recently been clarified by investigations we have carried out in collaboration with the German Museum in Munich. The process affects chiefly glass that has a large content of iron and manganese (glass, as it happens, from the Romanesque and the early Gothic period). First the uppermost, fire-polished layer of the glass is furrowed by crizzling: a great number of microscopic fissures, which allow oxygen, moisture and acids to penetrate. The result (in contrast to the more typical corrosion, which produces a weathering crust) is the stripping of electrons from chemical elements such as iron and manganese. The resulting chemical products tend not to dissolve. Also, they are dark brown. They actually cause stained glass to turn black and opaque. To a degree the process can be reversed (in places where there is no grisaille on the glass) by the use of reducing agents to undo the oxidation.

The ideal solution, impractical in most churches, would be automatic, year-round climate control combined with air purification. A less extreme solution is the provision of a micro-climate around the church's stained glass, independent of the conditions elsewhere in the building. Double glazing helps. The protective glass, firmly sealed in the position of the original stained-glass window, absorbs fluctuations in external temperature and provides a cooling surface. (At low exterior temperatures it collects moisture on the inner side; at low interior temperatures the moisture collects on the outer side.) The stained glass, hung in the church next to the protective glass, is exposed to the air in the building. It remains dry on both sides.

The body of knowledge accumulated so far will be an aid to future efforts. We ourselves, in collaboration with the German Museum, have published a damage atlas for the Federal Republic of Germany, encompassing stained glass from about 1520. As part of the project we have chosen 30 locations, and in each one we have recorded, over half a year, the local temperature, humidity and air pollution impinging on the medieval stained glass. The intent is to help save a heritage whose loss could otherwise be predicted within our generation

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Lucky and Unlucky Panel were both made by Michael Wohlgemuth, the teacher of Albrecht Dürer. The stained glass at the top, which depicts Lorenz Tucher, the donor, is from the Church of St. Michael in Fürth; it was made in 1485. Exposure to weather did it no harm. In 1815 it was sold and became part of a private collection. Finally, in 1968, the German National Museum in Nuremberg acquired it the glass is wholly intact. The stained glass at the bottom, which depicts the emperor Heraclius entering Jerusalem, is from the Church of St. Lorenz in Nuremberg; it was made in 1476-77. In the 19th century it was subjected to efforts at restoration that only damaged it further. Many Parts of the panels are 19th-century copies of the original pieces of glass. Moreover, the face of the emperor and the face adjoining it have fractured into hundreds of splinters; they are intact because the heads were laminated at the back.

Micrographs of stained glass show further details of detoriation. Pitting (upper left) Pocks the surface of glass from Augsburg Cathedral. The enlargement is 25 diameters. The bottom of a pit (upper right) shows the advance of the decomposition under the influence of humidity. The enlargement is 1, 000 diameters. The decomposition of the surface of a pane from the monastery at Lorsch in Germany (bottom left) has exposed a scarred understatum of glass. The enlargement is 10 diameters. Deep fissures (bottom right) have formed in glass from the church at Lauterbach in France. The smoothness at the upper right is the original surface, preserved in that location. The enlargement is 600 diameters.

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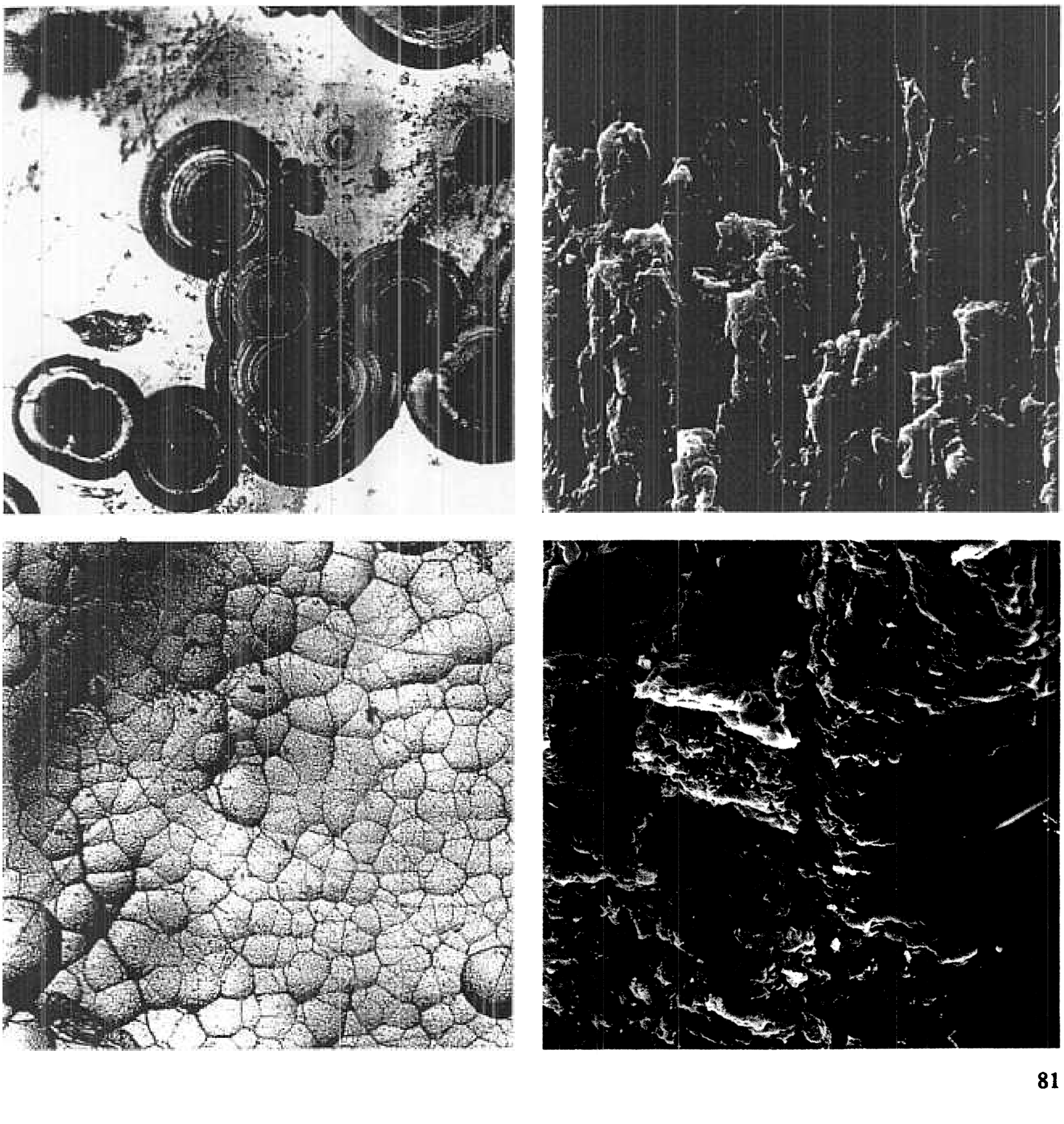

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St. Ambrose was depicted by Wohlgemuth in 1477 for the Church of St. Lorenz in Nuremberg. Since then the history of the glass has been particularly unfortunate. In 1836 the glass painter and restorer Johann Jakob Kellner replaced the banderole, or decorative scroll, that bears the name of the saint. A century later it became apparent that all the painted linework on the glass had flaked off; it had been undermined by corrosion. An effort to reattach the paint by refiring the glass served only to melt and blur the hatch lines. In addition white glass took in a yellow-brown hue and glass used for the robe of the saint, which had been blue, turned black. The fine painted detail is now visible only as a negative image.