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Figure 1 Leonardo da Vinci, *Cartoon: The Virgin and Child with S. Anne and S. John the Baptist* (No.6337), paper mounted on to canvas. After restoration.

The Restoration of the Leonardo Cartoon

Eric Harding, Allan Braham, Martin Wyld and Aviva Burnstock

Introduction

Allan Braham

Leonardo's Cartoon of the *Virgin and Child with S. Anne and S. John the Baptist* (No.6337; Plate 1, p.26 and Fig.1) was presented to the National Gallery by the National Art-Collections Fund in 1962, following a public appeal towards what then seemed an almost unattainable sum (£800,000). Since that time the Cartoon has remained amongst the most popular works in the Collection, seen by millions in the original, and familiar from reproductions to those who have been unable to visit the National Gallery. Widespread public concern followed the news that on 17 July 1987 the Cartoon had been seriously damaged by a blast from a shotgun, aimed at the breast of the Virgin. The papers that follow in this issue of the *National Gallery Technical Bulletin*, by the Chief Restorer Martin Wyld and by Eric Harding, from the staff of the British Museum, outline in detail the measures that were taken to assess the nature of the unprecedented damage caused, and the careful process subsequently followed to restore the Cartoon, which went on show to the public again in May 1989.

Since the time of the acquisition of the Cartoon in 1962 more has been learnt about Leonardo (1452–1519) and the place of this particular drawing in the evolution of his work. More can also now be surmised — as a consequence of the treatment it has undergone — about its original appearance and its history. It was once widely assumed that the Cartoon had been produced probably about 1497–99 in Milan, where Leonardo had moved in or just before 1483 [1], and that it preceded the cartoon of the Virgin and Child and S. Anne of 1501 described in early sources, which was the first major work produced after Leonardo's return to Florence [2]. A Milanese origin for the Cartoon is clearly suggested by what is known about its early history, and by the existence of a painted version, which includes the figure of S. Joseph, by Bernardino Luini (Fig.2).

An alternative dating of about 1506–8, after Leonardo had returned to Milan, has meanwhile gained general agreement, or more precisely that the drawing may have been made in the winter of 1507–8. The artist spent some months in Florence then, and its influence can be traced there, especially in works by Raphael, who was never in Milan [3]. The sequence of Leonardo's ideas on the theme would therefore have begun with the cartoon of 1501, which is probably recorded in variants painted by Andrea del Brescianino (Fig.3), continued with the London Cartoon — first sketched in a drawing in the British Museum (Fig.4), and concluded with the painting in the Louvre, probably of 1510–15 (Fig.5). In this, Leonardo returned to his first idea, to the extent of including the lamb and omitting the figure of the Baptist as well as the pointing gesture of S. Anne, but he reversed the figures and integrated them more coherently than before.

Confirmation for this revised dating of the Cartoon is to be found in the British Museum drawing, not only in the character of its draughtsmanship, but because the hydraulic studies that it also shows, as has recently been pointed out, are related to others made by Leonardo in the period 1506–8 [4]. The direct influence on Leonardo of classical art also intensified in the first decade of the sixteenth century and statues of the familiar kind that represent seated Roman matrons must have inspired the figures in the London Cartoon [5]. This aspect of the work was felt particularly by Kenneth Clark at the time of the Leonardo appeal in 1962, 'The flow of the draperies and the grand ample movement of the figures has the quality of Greek art at the moment of its highest development [. . . .] Leonardo wanted to recapture the smoothness and perfection of the Greek ideal and add the sense of inner life.' [6]

The main change to the appearance of the Cartoon following the recent restoration is the recovery of the edges of the paper at the top and sides after the removal of the wooden stretcher (Fig.6). Though only about 1.25 cm in width these fragmented strips of paper have a significant effect on the perception of spaciousness in the composition, making it appear closer to the design of the British Museum drawing (Fig.4), where lines roughly indicate the relation of the figures to their proposed surroundings. The Cartoon may originally have been a little wider, and is probably trimmed on the left especially towards the base. Of the eight sheets of paper on which it is drawn, those to the right are wider than those on the left, the widest (that at the base) being about 560 mm, as distinct from the 510 mm of the sheet to its left (Fig.7). The measurements can only be approximate as the sheets are overlapped, and the exact limits of the edges not precisely visible. The vertical seam where the eight sheets join in the centre runs at a slight diagonal, top right to bottom left, which corresponds with the evidence of cutting suggested by the sizes of the separate sheets.

The presence of nails at the base of the paper, now removed but used to fix the paper and canvas to the stretcher from the front, suggests that the Cartoon was not trimmed at the bottom, but there may well have been more space above the heads of the figures. The two sheets of paper at the top (Fig.7) are about 150 mm at the tallest, and those at the base about 360 mm, but it seems unlikely that anything like 200 mm could be missing at the top. Though the approximate shape of the design is shown in the British Museum drawing, there would be no reason for the Cartoon to show much more than the

main figure group, as copied by Luini in his painting in the Ambrosiana (Fig.2) [7]. A fragment of the original figure drawing was revealed through the recovery of the edges of the Cartoon in the left foot of S.John. In addition the recovered edges give some impression of the degree of discoloration — probably less than might have been feared — to the Cartoon since the period when it was laid on canvas and on its stretcher.

Examination during the recent restoration suggested that the worst damage suffered by the Cartoon in the past was at the time it was given its canvas support. The extensive tearing in the paper, especially across the top corners and along the edges is consistent with the paper being put on to a pasted surface without having first been moistened (see the sections by Martin Wyld and Eric Harding below). Areas of weakness in the paper had been strengthened, no doubt at different times during the course of its early history, and in certain areas, notably the top corners and the centre of the right edge (Fig.8), the paper now visible is not that of the original. An experiment with turning back the canvas at the top left revealed that a print had been used for patching, an etching probably Italian and of the late sixteenth century, showing eight of the Emperors of Rome with six of them fully visible (Fig.9). They are named and shown in numbered rectangles in the sequence [12], 24, 4[–], 58, 75?, 92, 109 and 130. The sheet must be an extensive one, and presumably shows the Emperors in rows of twelve (with some of the portraits of later, short-lived Emperors evidently missing) [8].

It seems likely that this sheet, at least, and the others now extensively visible as parts of the surface of the Cartoon were added at the time that it was pasted on to canvas, though how exactly the whole clumsy process was carried out cannot be clearly reconstructed. Judging by the date of the print, the work must have taken place not before the late sixteenth century, and the appearance of the canvas and stretcher suggests a later period. It seems unlikely that the Cartoon was subjected to the process of being put on a canvas and stretcher on more than this one occasion in the past.

The Cartoon appears to have remained in Milan until passing to the Sagredo Collection in Venice before April 1726 [9], and it may well be that it was equipped with its canvas backing and the stretcher to make it easier to transport at that time. Alternatively the process may have been carried out in Venice before the Cartoon was shipped to London, probably before Christmas 1763. The presence of the print on the reverse suggests that it was not pasted to its canvas after its arrival in England, where it is first recorded for certain in possession of the Royal Academy of Arts in 1779.

Figure 2 (Right, top) Bernardino Luini, *Holy Family*. Ambrosiana, Milan.

Figure 3 (Right) Andrea del Brescianino, *The Virgin and Child with S. Anne*. Berlin.

Figure 4 Leonardo da Vinci, *Studies for the Virgin and Child with S. Anne*, pen and ink on paper. British Museum, London.

Figure 5
Leonardo da Vinci,
The Virgin and Child with S. Anne.
Musée du Louvre, Paris.

Figure 6
The Leonardo *Cartoon* (No.6337).
Detail of the top right-hand corner, after restoration, showing the recovered edges.

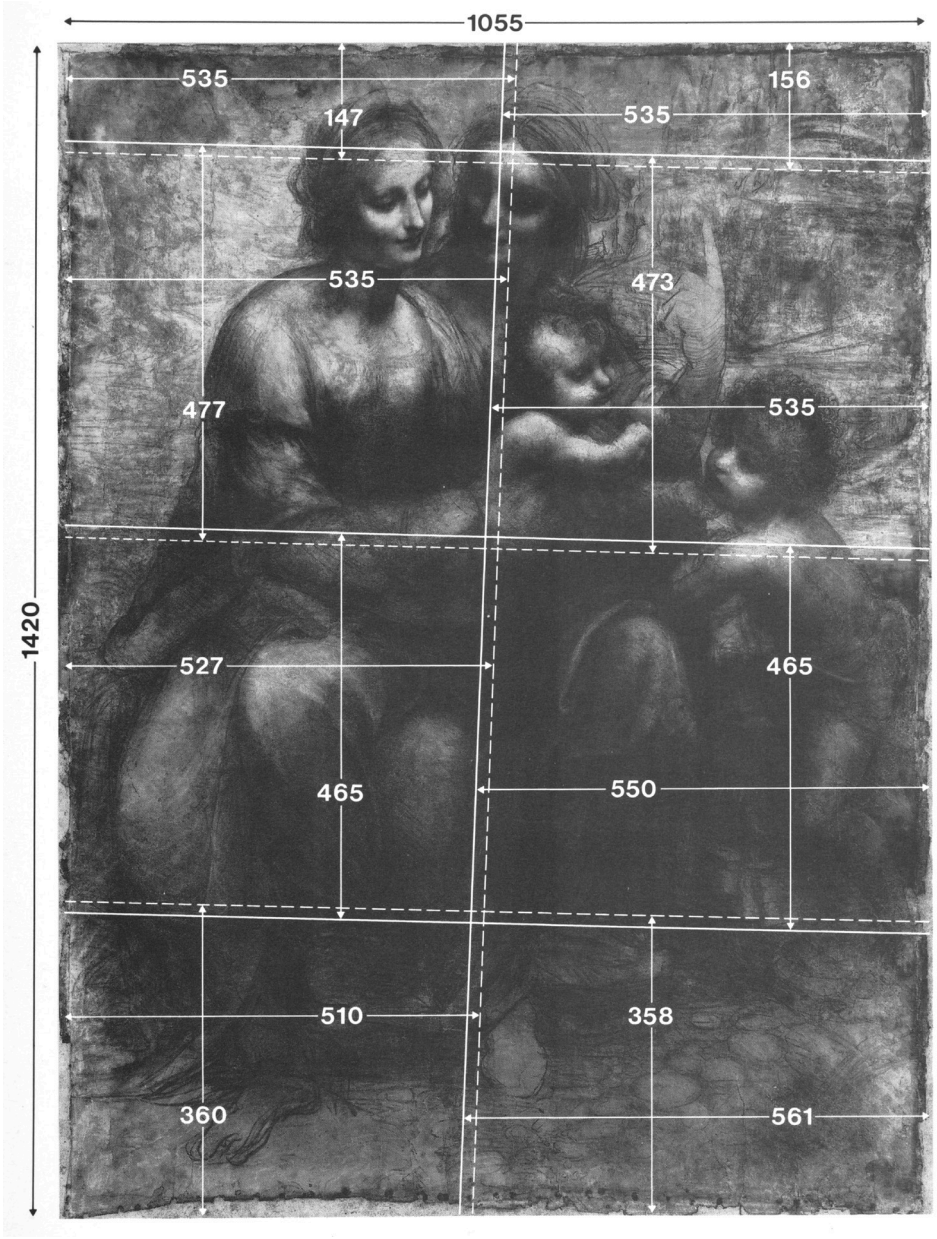

Figure 7 The Leonardo *Cartoon*. Diagram showing the overlapping sheets making up the whole. Continuous lines = paper edges; broken lines = extent of paper at joins. Dimensions include flattened edges, all measurements in millimetres.

Figure 8 The Leonardo *Cartoon*. Diagram showing patches and losses. After restoration. RP = repair patch (behind drawing); L = loss (old, toned infill); broken lines = possible additional repair/support patches; shaded area = shotgun damage.

Notes and references

1. Clark, K., *Leonardo da Vinci* (1939) (1958 edition, p.105); Popham, A.E., *The Drawings of Leonardo da Vinci* (1946), pp.72–3; Davies, M., *National Gallery Catalogues, Acquisitions 1953–62* (1963), p.51; and more recently Wasserman, J., *The Art Bulletin* (1971), pp.213–25.
2. See, most recently, Kemp, M., *Leonardo da Vinci* (1981), pp.220–27; and Pedretti, C. in exhibition catalogue: *Leonardo e il leonardismo a Napoli e a Roma*, Naples, Museo di Capodimonte (1983–84), p.50.
3. The move towards a later dating began with Popham, A.E. and Pouncey, P., *Italian Drawings of the 14th and 15th Centuries [. . .] in the British Museum* (1950), no.108, followed by Clark, K. and Pedretti, C., *The Drawings of Leonardo da Vinci [. . .] at Windsor Castle*, Vol.1 (1968) p.95, no.12526. See more recently Pedretti, C., *Leonardo* (1973), p.104; Gould, C., *Leonardo* (1975), pp.162–54 (influence on Raphael); Kemp, M., *op.cit.*, p.225.
There is no indication that the London Cartoon was used for a painting; late in the sixteenth century it was accepted that cartoons acted as finished works of art, and 'sub-cartoons' for direct use for paintings were commonly made (see Cappel, C.B., *Master Drawings*, **XXV**, 2 (1987), pp.131–42).
4. Kemp, M. in exhibition catalogue: *Leonardo da Vinci*, Hayward Gallery, London (1989), p.150.
5. Pedretti, C., *op.cit.* (1973), pp.105–6, refers more precisely to the Muses of the Villa Madama.
6. Clark, K. and Gould, C., *The Leonardo Cartoon* (1962), p.6.
7. The interesting theory had been propounded by Dr Milo Keynes that the figure of S.Joseph may originally have been present in the London Cartoon, as in Luini's painting. The present condition of the Cartoon in the top right corner (see further below) appears to be too poor for this idea to be easily confirmed. It is to be hoped that Dr Keynes's paper on the subject will soon be published.
8. The print has been identified as an etching, probably Italian and of the late sixteenth century, by Anthony Griffiths of the British Museum, who suggests that it is from what is known as a *Chronologie Collée*, a kind of production more common in France than in Italy, which has not yet been fully investigated. It refers to large sheets of prints intended to be cut out and pasted on an accompanying sheet of letterpress.
The first of the Emperors shown, no. [12], is presumably G[ALBA], who was sixth after Augustus, in which case the series presumably began with the six legendary Kings of Rome who followed Romulus. Following that of Galba, names that can be identified on the print are S.GETA, no.24 (209–211 AD), TACI[TVS], no.4[–] (275–276 AD), ARCA[DI]VS, no.58 and CONS[T]ANS, no.75. The last two names are more difficult to identify, apparently LO[T]ARIV[S], no.92, and HEI[ ]R . . ., no.109. The name for no.130 is not visible.
9. On the history of the Cartoon see Davies, M., *op.cit.*, p.53–54.
The maximum size of the Cartoon is now approximately 141.5 × 106.5 cm.
On the technique see further Aviva Burnstock below.

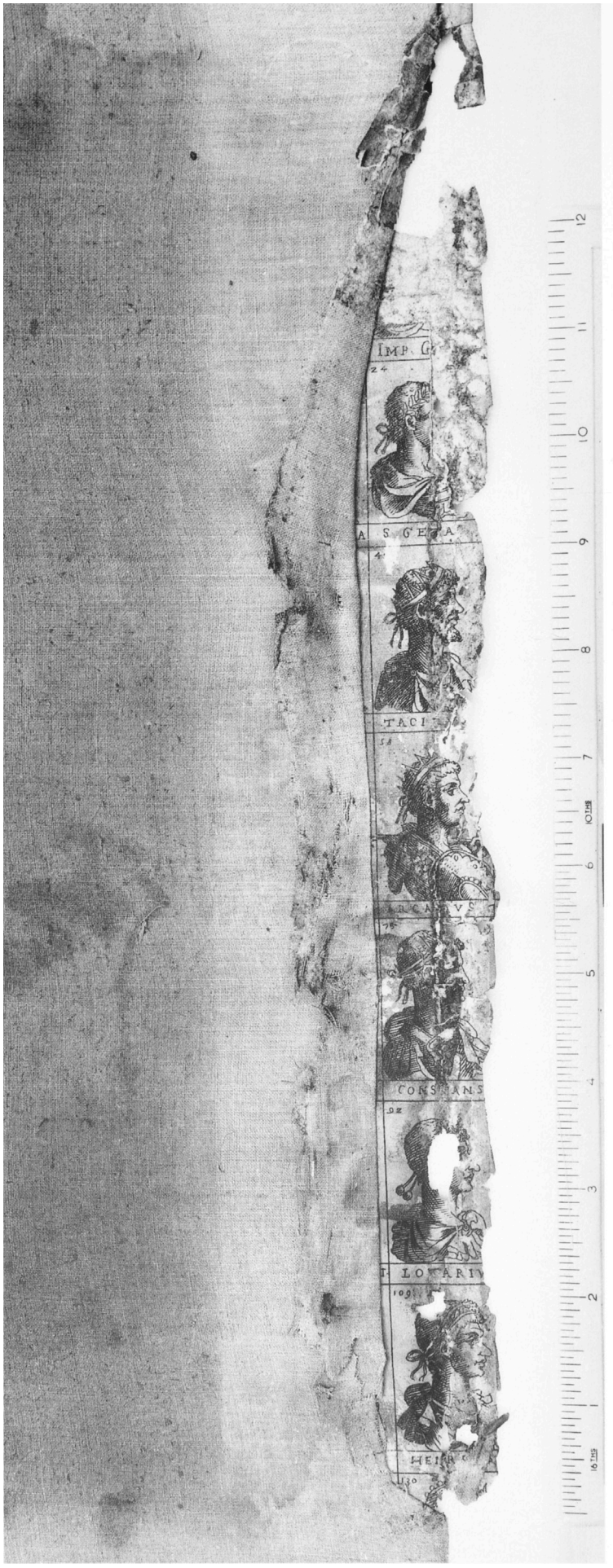

Figure 10 (Right)
The Leonardo *Cartoon* in raking light, after repair. The overlapping joins, patches, tears and wrinkles, and the vertical folds at the sides are clearly visible.

Figure 11 (Below)
Beta-radiograph (actual size) showing the chain and laid lines of the original paper of the *Cartoon*. These features are rather obscured by the degeneration of the paper structure. (See also Figs. 19 and 22.)

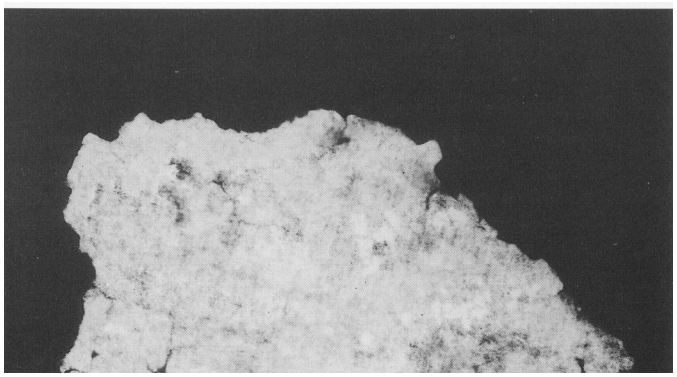

Figure 9 (Left) Detail of the etching showing Emperors of Rome on reverse of Leonardo *Cartoon* (top left), probably Italian, later sixteenth century.

The history of the Cartoon

Martin Wyld

The original materials

Leonardo used as a support eight rectangular sheets of linen rag paper glued together with overlapping joints (Figs.7 and 10). The creamy-white paper was probably given a preparatory coating of red-brown iron oxide pigment mixed with a little carbon black and calcium sulphate. The image was drawn in charcoal (carbon black) heightened with a white 'chalk' (calcium sulphate). The recent repair of the Cartoon has provided an opportunity to examine the original paper by beta-radiation [1], and for the first time an image has been obtained of the chain and laid lines (Fig.11); this is described in the fourth part of the article.

Figure 12 The Leonardo *Cartoon* by transmitted light, after damage, showing the long tear at the left edge caused by unskilful handling when it was laid on to canvas. The fragmentation of the paper around the area of impact can also be seen.

Earlier restorations of the Cartoon

Very few large Renaissance drawings or cartoons have survived until the twentieth century; the majority were not intended to be preserved. The inherent fragility and impermanence of paper as a support, particularly when many sheets are glued together, and the tendency of paper to become acidic and brittle with age, in combination with the vulnerability of charcoal and chalk to abrasion have also led to the loss of the great majority of such works.

There are no records of treatment or repair to the

Cartoon until the late eighteenth century, but it had probably been torn and patched by the late seventeenth or early eighteenth century [2]. The main patches on the back of the original paper are shown in Fig.8. It is not known if the patches were applied simultaneously. The paper of the patches in the bottom right corner and at the centre of the bottom edge are similar but are different from that of the patch in the top left corner. The strip patches beneath the tear in S. John are not accessible and no examination of them has been possible. During the recent repair the patch in the top left corner was discovered to be a print of the heads of Roman emperors (see the first section of this article; Fig.9).

The Cartoon, with all its patches, was laid on to canvas before it was transported to England in the 1760s. The laying-down was not done skilfully; the Cartoon shrank and wrinkled violently, and clumsy attempts to flatten it tore away most of the left edge which was then pushed roughly back into place (Figs. 10 and 12). The fragility of the paper would have made flattening of the wrinkles impossible, and they still show clearly in raking light.

By the time the Cartoon came to England in the mid-eighteenth century it had been restored with chalk and charcoal similar to the original materials and probably also with white lead and watercolour. Further restoration was done at the Royal Academy in 1791 and 1826, when zinc white, a pigment introduced in the late eighteenth century, may have been used. Minor restoration was necessary in 1962, when the Cartoon was slightly damaged during the public appeal for its acquisition by the National Gallery.

Following the acquisition of the Cartoon by the Gallery in October 1962, the Trustees resolved to invite an International Committee of experts to advise them on the Cartoon's condition and on the safest method of displaying it. The Committee found that, 'on the whole the Cartoon's state of preservation could even be described as good, considering its size and the vicissitudes it had undergone in more than four and a half centuries'. They found the support to be 'somewhat inadequate' but in view of the danger and difficulty of removing the canvas from the stretcher and the virtual impossibility of removing the paper from the canvas using available techniques, thought that, 'the whole support to the drawing now has to be considered as one'. They found the paper to be 'weakened by a highly acidic condition making it brittle and fragile'. They stated that at present there was no safe method known for extracting the acid from the paper, but that they did not consider this question urgent provided that the other recommendations for reducing the strain on the paper were put into effect. These included protecting the Cartoon from movement and vibration, and keeping it in conditions where light and relative humidity could be closely controlled and atmospheric pollution reduced to a minimum. The Committee, in consultation with the Gallery's Chief Restorer at that time, made recommendations for some minor repair work and for additional support to be given to the canvas by fitting into the stretcher a padded bed which would also reduce vibration and strengthen the Cartoon against accidental damage.

With regard to the safekeeping of the Cartoon, the Committee subscribed to the following general principles:

> The Cartoon is to be on permanent display, and it must also be kept safe for future generations. The opposition between these two aims is the central problem of museum conservation. In the present case the problem divides itself into three parts: (1) Humidity variation is the chief cause of movement within the structure of the Cartoon. Every time the humidity changes, such a moisture-sensitive object expands, contracts or warps; and eventually such movement causes cracking, breaking, detachment of small pieces, etc. Humidity variation is almost eliminated by efficient air-conditioning, which is therefore essential in the Cartoon's final display. (2) Oxidation of the paper is caused by the combined action of air and light. Briefly, to minimise the effect of this oxidation through the action of light, all the invisible ultra-violet light will be removed by placing a colourless UV-absorbent filter over the light sources, and the intensity of the visible light will be controlled to be just above the minimum for clear viewing (50 lux is suggested). (3) As has been seen, the oxides of sulphur present in all urban atmospheres are mopped up by paper: they are the major cause of the acidity of old paper, and directly lead to its embrittlement. Fortunately, an air-conditioning system of the type installed in the National Gallery effectively removes sulphur oxides, since the air passes through a permanent water spray.

Following the recent damage, comparison of the Cartoon with detailed photographs taken in 1962–63 showed that there had been no detectable deterioration since the Cartoon's acquisition. The changes in the Cartoon's appearance before its acquisition have been considerable. The original paper has darkened, discoloured and been stained by water running down it, and by adhesives. The paper has also been severely torn, completely lost in places, patched with darker paper of different texture (Fig.8), folded down the sides (Fig.10) and has wrinkled. Some of the original charcoal has been lost, and the original white chalk heightening appears to have been loosened and washed haphazardly over the top half of the image, where it is mingled with lead white used in an early restoration. A variety of other materials have been used to retouch *lacunae* and tears in the paper, and to reinforce abraded areas.

The recent damage

In the attack of 17 July 1987, the 'unbreakable' laminated glass partly withstood the pellets from a sawn-off shotgun fired from approximately seven feet. Although the inner layer of glass was shattered and pushed into the Cartoon, the pellets bounced back into the room; none of them penetrated the Cartoon itself. The glass was pulverized and, as it was pushed in by the force of the shot, struck the Cartoon a sharp blow on the Virgin's breast in an area about 150 mm across. Advice later given by the Metropolitan Police Forensic Science Laboratory indicated that had the gap between the glass and the Cartoon been larger the damage sustained would have been more severe. The cushioned backboard which had been fitted behind the canvas and inside the stretcher bars in 1962 absorbed some of the impact. The canvas was stretched and slightly torn, but the brittleness of the paper led to a series of concentric tears (Figs.13 and 14) and to some paper becoming detached. The damage was worst not in the area of impact itself but in the adjoining part of the Cartoon, particularly above and to the right

Figure 13 (Left) Detail under ordinary illumination, after damage.

Figure 14 (Below) Detail of the damage in raking light.

of the impact. Paper was loosened from the canvas, but not detached, outside the concentric tears visible in Fig.14.

Assessment of the damage a few minutes after the shot had been fired was difficult because of the pulverizing of the glass and its consequent opacity. The long cracks extending from the area of impact proved, fortunately, to be confined to only one layer of the three-layer laminate and therefore not likely to lead to the collapse of the whole sheet of glass and further damage to the Cartoon (Fig.15). As soon as police procedure permitted, the Cartoon was first removed from the display panel and then from its frame. Many detached fragments of paper were recovered from between the glass and the mount at the bottom of the frame.

Possible methods of repair

The National Gallery Collection contains very few works on paper and its Conservation Department has no expertise in paper conservation. Help was sought immediately from other national institutions with relevant experience and knowledge. An informal group of paper conservators from the British Museum, the Victoria & Albert Museum, the Royal Library at Windsor and the Tate Gallery was brought together within days of the attack. Its members examined and discussed the Cartoon both individually and as a group. Many paper conservators from other institutions and from private practice generously offered their help and advice, and visited the Gallery to examine the damage. The paper conservation profession as a whole showed enormous sympathy to the Gallery and concern for the Cartoon itself.

Informal discussions between the group of paper conservators and Gallery staff established that, broadly, two approaches to the repair of the Cartoon were possible. Firstly, to repair the shotgun damage, confining treatment to the damaged area alone, but possibly removing the canvas from the stretcher. Secondly, at the same time as repairing the shotgun damage, to attempt the radical treatment rejected by the International Committee in 1963, involving removal of the canvas, glue and patches from the back of the original paper, followed by de-acidification and remounting of the Cartoon on a buffered backing.

Meetings with the paper conservators continued for several weeks, and many significant factors concerning the repair of the shotgun wound and the prospects for the long-term preservation of the Cartoon were comprehensively discussed. The damage to the Cartoon was thought to be unprecedented. None of the conservators had either repaired a similar damage or had knowledge of such damage occurring elsewhere. There was little experience of even ordinary conservation work on chalk and charcoal drawings attached to canvas and of comparable size to the Cartoon, and there was general agreement that the repair of the Cartoon would be an awkward task.

The factors which made the Cartoon difficult to treat were all commonplace, but in combination became daunting: the very high acidity and brittleness of the eight sheets of original paper, the number and size of the patches on the back, the reinforcement with glue and canvas of high acidity, the fragility of the charcoal and chalk medium, and the extent of the old restoration on the surface. Taken together with the devastating nature of the damage, the condition of the Cartoon presented a formidable problem.

Discussion of the restoration of the Cartoon ranged from the narrowest details of how the pulverized glass might be removed from the fragments of paper to the broadest consideration of long-term preservation, the feasibility of de-acidification and the ideal conditions for future display. Removal of the canvas and glue was seen to be theoretically desirable; so was de-acidification of the original paper. The very high acidity of the paper, and its consequent embrittlement and discoloration, was thought to result from atmospheric pollution, natural ageing and to the glue and canvas behind.

Much discussion centred on de-acidification — its physical and chemical effects, both short and long-term, and on methods of achieving it [3]. There was general agreement that whatever method of removing the canvas and glue was used, the Cartoon itself would have to be wetted with either water or solvents if it were to be de-acidified. Dry removal of the canvas and glue on the back of the Cartoon (with the Cartoon face-down) would lead to a great risk of chalk and charcoal being shaken off the front. The damaged area, even if the loose paper fragments had been removed, would be very vulnerable to further distortion and fragmentation. If

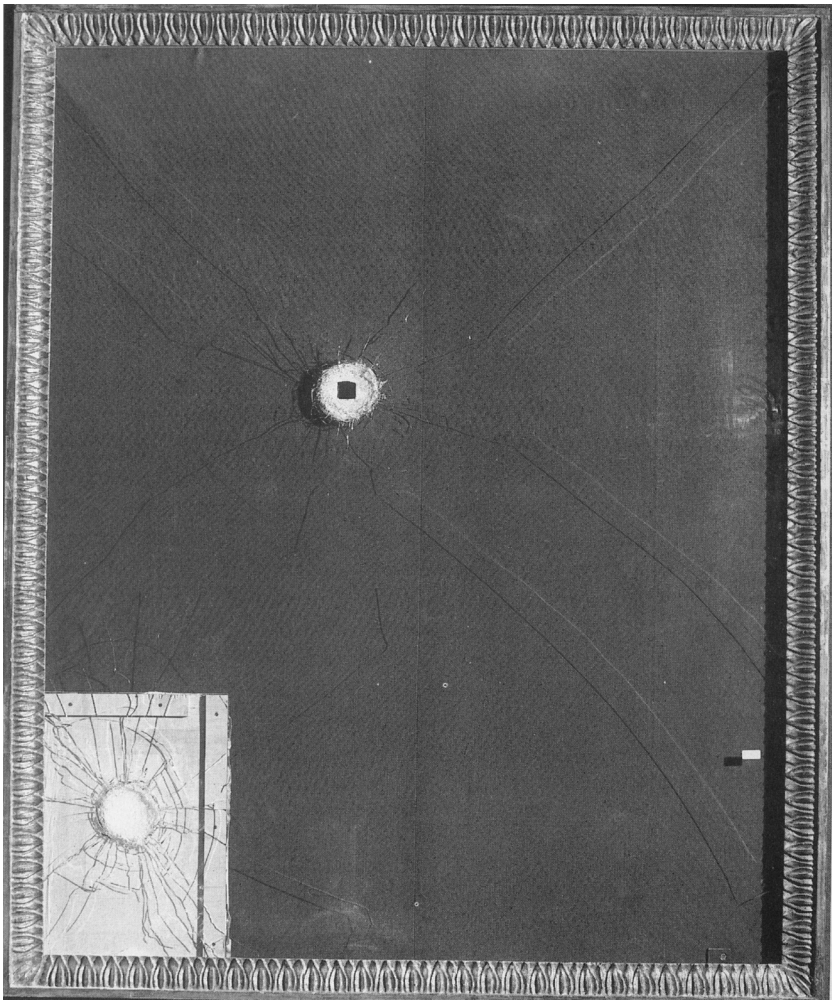

Figure 15 The laminated glass showing the effect of the shotgun blast. The test sample after the shot by the Metropolitan Police Forensic Science Laboratory can be seen in the lower left corner.

the canvas were to be taken off after the glue had been softened in a humidity chamber (or by another method of introducing moisture) the Cartoon could become very difficult to handle, since the longest tears (at the left edge) were supported only by the canvas. The patches in the corners and under the tear through S. Anne, the Child and S. John might become detached, and the original overlapping joins, many of which were very insecurely stuck, might also lose adhesion. A further danger was that the moisture used could change the refractive index of the highlights in white chalk, which had already been affected by past treatment, and also produce light or dark stains on the surface of the Cartoon. The process of de-acidification itself would also expose the Cartoon to these dangers, and might have a considerable effect on its appearance. In addition, the paper might lighten dramatically, and much of the restoration be removed.

The National Gallery staff who took part in the discussions about the repair of the Cartoon were convinced of the theoretical desirability of de-acidification. However, the risks described above were judged to be unacceptable in the treatment of any object in the Collection. The probability of uncontrollable and irreversible changes in the appearance of the Cartoon outweighed the gain which would have resulted from de-acidification. The risks associated with canvas removal and de-acidification could only have been justified had the Cartoon been in imminent danger of destruction, and that was not the case. If, when the Cartoon was crudely laid on to the canvas, a paper interleaf had been used, the removal of the canvas would have been a much safer undertaking.

No clear answer could be given to the crucial question of how much the Cartoon could decay if it were not de-acidified. The acidity of the original paper had been tested in 1962 and was tested again in 1987. The results were similar — a pH of 3.3 ± 0.2 in 1987, compared with 3.5 in 1962. It seemed probable that the paper of the Cartoon had reached this level of acidity after it was laid on to canvas, and increasingly so during the course of the nineteenth and twentieth centuries.

The proposed method of repairing the Cartoon was explained to the National Gallery Trustees, and agreed by them. The Trustees also approved the choice of Eric Harding of the British Museum Department of Conservation (Western Pictorial Art) to carry out the repair of the Cartoon. His work is described below.

Notes and references

1. Mavis Bimpson, of the British Museum Research Laboratory, kindly undertook the beta-radiation examination.
2. Dr Julius Grant examined and identified some of the patching paper in 1963–64.
3. Petherbridge, G., *Conservation of Library and Archive Materials and the Graphic Arts* (London 1987).

The repair and restoration of the Leonardo Cartoon

Eric Harding

The shotgun blast, which severely damaged an area located close to the Virgin's right breast, created a unique and unpleasant precedent in the conservation and repair of a large and famous work of art on paper (see Fig.13). It also provided an opportunity to look again in depth, from a conservator's point of view, at the Cartoon's physical condition and to observe at close quarters the extent of previous work carried out on it.

The eight sheets of overlapped hand-made paper on which the Cartoon is executed has, over the centuries, become severely degraded for three principal reasons:

1. The crudeness of the seventeenth or eighteenth-century lining process which resulted in widespread fracturing and cockling (wrinkling) of the surface (Fig.10).

2. The absence of a paper interface between the back of the Cartoon and its canvas support. This has allowed unrestricted sulphur dioxide pollution of the assemblage to penetrate the canvas, and has greatly contributed to degeneration of old adhesives.

3. The poor condition of much of the old repair work, old restoration and retouchings.

Taking into account the age and general natural fragility of the medium and its support, it was important to avoid the temptation to move too hastily in an effort to rectify the appalling damage that the Cartoon had sustained.

The damage caused by the shotgun blast

Preliminary examination of the area of shattered surface (approximately six inches in diameter) found that no shotgun pellets had actually penetrated through to the Cartoon. This was due entirely to the toughened glass absorbing much of the impact. However, the smashed paper and canvas structure had been deeply penetrated by pulverized glass and larger glass fragments. The shock of the gun blast had caused many of the paper fragments to split into two layers with the lower layer still attached to the canvas and the upper layer lying loosely. The damaged area was grossly distorted, stretched and consequently misaligned. The canvas structure at the back was severely distorted and very weak. The tendency was for this area to sag downwards when lifting the Cartoon to examine the back.

Examination and assessment

Two major difficulties had to be borne in mind before any searching inspection involving fragment disturbance could be carried out. These were:

1. How to be reasonably certain of the identity and location of damaged fragments within the damaged area.

2. How safely to remove embedded and loose glass without causing mass movement of the small particles of Cartoon fragments.

Figure 16
Detail of finger mark fracture, top right.

These two problems formed the main preoccupation in the first weeks of evolving a method to deal with the Cartoon.

The first practical task involved long and careful microscopic scrutiny with associated documentation and macrophotography of the damaged area. This was followed by the removal of some of the larger glass pieces, some of which had paper fragments attached. These were removed and set aside for retrieval at a later stage. Meanwhile a large number of identical actual-size photographs of the damaged area were produced for the purposes of fragment location, as all fragments of paper and glass would need to be removed from the surface before any repair work could be contemplated.

Removal of fragments from the area of damage

The method employed was to identify and record on the photographs each fragment of the Cartoon intended for lifting from the damaged area. They were numbered in sequence and in order of removal, then placed in small transparent plastic boxes with the numbered photograph locations cut out and attached to the box lids. An uncut copy of the same photograph was used to create a full-scale numbered map showing where all of the fragments had originated (Plate 2, p.27).

There were many fragments which could not be located by this process, for example those rescued on the day of the shooting from the shattered glass, others from the Gallery floor, and those displaced by the force of the blast to the periphery of the drawing. These were dealt with during reconstruction, initially by comparing tonality of the various loose fragments with known areas, classified as light grey, grey, grey-black, black, and so on. They were then further categorized by shape, until their locations had been determined. In all there were about seventy larger fragments or fragment aggregates in individual boxes and about two hundred tiny pieces, many no larger than a pin-head. These mostly derived from debris beneath the larger fragments and from the general process of fragment removal.

Removal of glass

The first practical task involved the removal of the pulverized glass shards and particles from the damaged surface. This was achieved in dim light using fibre-optic cold lights. This caused the impacted glass particles to sparkle brightly, assisting their location and removal. A vacuum-suction tweezer unit proved invaluable for this purpose. Much powdered glass was also found within the loose fragments and their fibres.

The old lining

The Cartoon is laid directly on to canvas with no paper interface. The adhesive used in the early lining process was a mixture of animal glue and wheat-starch paste, an adhesive used commonly in old linings of easel paintings. In a raking light photograph it can be clearly seen that the lining process has produced many defects resulting in a large number of blisters and areas of cockling (Fig.10). This was primarily due to the Cartoon having been directly laid on to its pasted canvas support without any pre-moisturizing, a necessary step to protect the dry paper of the Cartoon from the effects of differential absorption of moisture from the paste layer. As a result, distortions and ruptures of the paper surface can be seen, caused by attempts at straightening out the twisted paper surface before the adhesive had dried (Fig.16).

The flattening process: test sample

With all fragments safely removed and stored it was possible to consider ways of dealing with the severely distorted and damaged canvas support, particularly how to flatten and reform the canvas fibre structure.

A vital step in the restoration process involved the design of a test piece. This was necessary in order to try to reproduce a damaged facsimile to experiment upon. Paper and canvas similar to the Cartoon were found and pieces were bonded together. They were then placed on to a wooden stretcher and subjected to mechanical stress by hammering with a heavy object. In this way it was hoped to simulate the impact. However early experiments proved only partially successful and it became

obvious that comparable damage was not being produced. It was decided, therefore, to ask the Metropolitan Police Forensic Science Laboratory if they would consent to shoot at a test piece, using a twelve-bore shotgun similar to the weapon used in the attack on the Cartoon.

This test piece was prepared and artificially aged in the Scientific Department. It was then attached on a stretcher to the back of the original Cartoon frame in the corner where the glass laminate was relatively undamaged. The shot was fired and the result was remarkably similar in effect, creating the ideal simulated damage including the pulverized glass (see Fig.15).

After a series of trials it was found that by using a specially modified low-pressure vacuum suction device in combination with an ultrasonic humidifier it was possible to reduce the most severe distortions to little more than gentle undulations. After this treatment it became apparent that the fragmented structure could gradually be returned to a flat plane with realignment of both paper surface and canvas support.

These series of experiments provided essential experience before work on repairing the Cartoon itself could begin.

Flattening process: the Cartoon

In the summer of 1988, immediately following the successful flattening of the artificially-aged test piece, the identical technique was applied to the Cartoon.

A structure was erected to support the Cartoon horizontally and the low-pressure vacuum suction device placed immediately beneath the damaged area. A winding mechanism had been built in, so that small custom-made perforated plates could be gently raised to the required position, thus limiting the need to move the whole structure. Ultrasonic humidity was then applied over the rear of the damaged canvas gradually softening and slightly moisturizing from the centre of the damage outwards to its perimeter and just beyond. In view of the extremely delicate nature of the charcoal/chalk medium, application to the front of the Cartoon had to be very brief, just enough to balance the treatment to the reverse. The deep distortions were slowly and gently coaxed outwards and into correct alignment with the aid of a tiny stainless steel flat spatula, in conjunction with applied ultrasonic humidity. About 10–15 millibars of low-pressure vacuum suction was needed to control and hold the newly positioned surface. After many hours of this treatment, the desired softer undulations were achieved in the damaged area of the Cartoon (Plate 3, p.27).

This was followed by a further application of ultrasonic humidity and full-power vacuum suction pressure on the Mitke unit to achieve complete flatness.

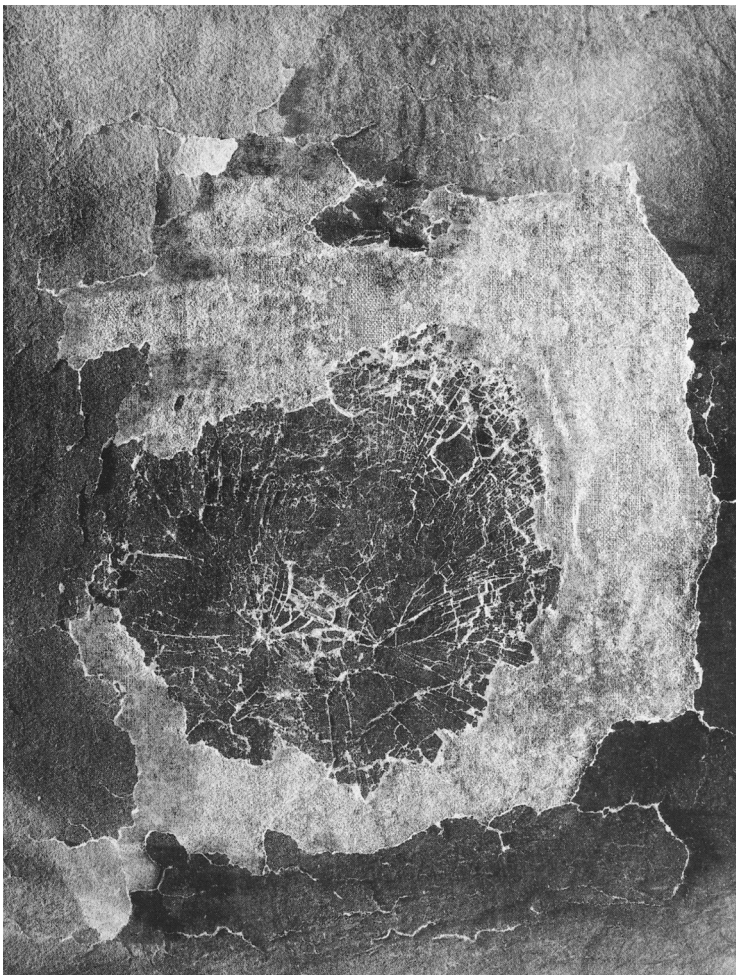

Figure 17 (Right, top) Detail of damage after removal of glass fragments and loose paper, and after flattening of the canvas.

Figure 19 (Right) Detail of the top left corner in raking light showing the recovered edges and the area of loose original paper examined by beta-radiography.

Removal from the old stretcher

The damaged area of the Cartoon was now flat (Fig.17) and could be safely handled, and in order to proceed to the next stage in the repair work it was necessary to remove the Cartoon's old wooden stretcher for a number of reasons:

1. The stretcher was made of very thin pine wood and had been further weakened by the removal, many years ago, of its vertical cross-member and corner supports (Fig.18).

2. The old tacks/nails pinning the Cartoon around the turnover edges had corroded to a point where they were causing serious deterioration of both paper and canvas.

3. The drawing appeared to extend in certain places to the extreme edges of the turnover.

4. To carry out a full additional lining necessary to strengthen the Cartoon, since the application of a patch to the damaged area was not desirable (see below).

5. The overall condition of the Cartoon, as seen in raking light, was such that considerable additional work was needed. Much of the very old repair work was showing signs of serious delamination and lifting (Figs. 10 and 19).

After the old tacks had been extracted, the hardened edges of the Cartoon and its canvas were straightened out, using 'ultrasonic humidity' followed by gentle pressure from weighted plate-glass strips. During the course of this work it was found that the top-left corner of the Cartoon (near to the Virgin's head) was supported by an old repair in which a Renaissance print had been used, blank side towards the canvas, with the corner of the Cartoon attached to it. This etching of Roman Emperors covers a good deal of the corner area. The extent of the print repair could not be fully ascertained because of risk to the Cartoon and therefore inspection was restricted to uncovering a strip 325 mm × 30 mm (see Fig.9). Afterwards this strip was reunited with the canvas using wheat starch adhesive.

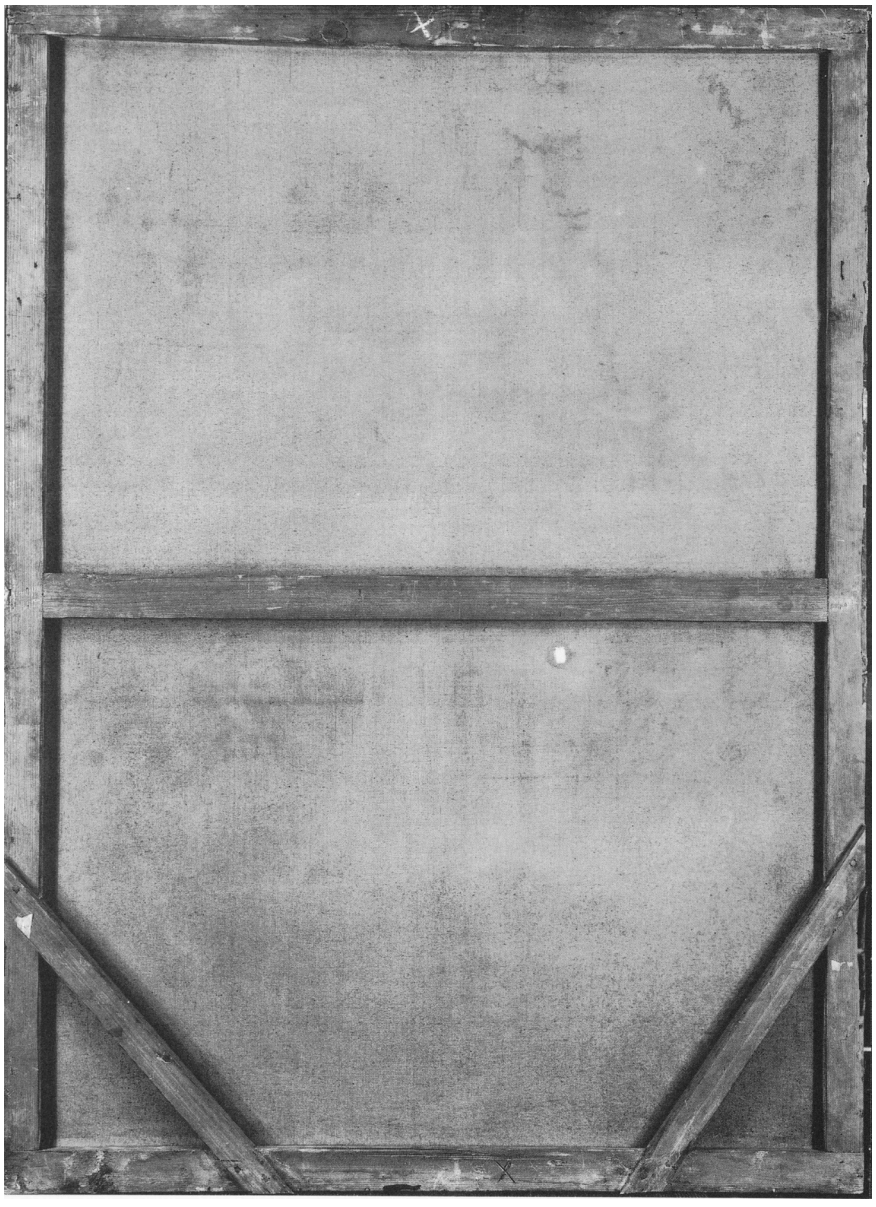

Figure 18
The back of the *Cartoon* before damage.

Work on the test samples

Once the shotgun damaged area on the test piece had been successfully made flat and the canvas structure reformed, methods of consolidation of this inherently very weak area were considered. Initially it was hoped that a thin Japanese paper repair patch might provide enough strength to hold the area, thus avoiding the need for a complete relining. However, even the thinnest Gampi tissue patch produced a ridge which could be seen in relief through the paper and canvas structure. It also produced a concave or saucer effect in the area as a result of 'drag' from the adhesive. With further experimentation along the same lines it become obvious that a local repair would not serve for the Cartoon.

The new support

The damaged area of the Cartoon, although now flat, was, as in the test piece, inherently very weak. It was decided that a full additional lining of Irish linen and acid-free semi-absorbent rag paper would be used and that this would be likely to benefit the Cartoon as a whole. This work was carried out using Japanese gluten-free wheat starch adhesive buffered with calcium hydroxide, which would be compatible with the original lining and would counteract, to some extent, the acidic nature of the Cartoon. In the process, the pH was improved from 3.3 before treatment to *c.*5.0 after relining.

There followed many weeks of testing samples of adhesives with bonded test samples for absorption rates and reversibility. Eventually a framework (loom) was prepared and covered with Irish linen and acid-free rag paper. Once dry and bonded together, the paper surface was coated with the wheat starch adhesive. The Cartoon, complete with the early canvas support, was then placed on to the pasted rag paper and the entire arrangement transferred to the low-pressure vacuum suction table for overall bonding. Dimensional stability of the Cartoon during this process remained unaffected because of the still attached old lining canvas. This meant that pre-moisturizing was not necessary.

Return of the fragments

Following the successful completion of the relining, the fragments could then be returned to the Cartoon (Plate 4, p.27). The technique employed was to apply wheat starch adhesive to the exposed canvas support within the damaged area, and with each fragment placed and positioned under magnification using a surgical needle and tweezers. Light pressure applied through tissue and siliconized paper effectively bonded the very thin fragments to the pasted surface. This was followed by a short period under gentle weighted pressure.

Many of the fragments had been displaced by the blast and were both distorted and out of position. There were also a large number of very tiny fragments of unknown location. Identifying these for the purpose of replacement was carried out by making tonal comparisons with fragments from a known position, for example by dividing the damaged area by eye into four parts. By using a known fragment from each quarter it was then possible under the microscope to compare the gradation of tone and thereby identify which quarter the tiny pieces came from. These were then integrated into the damaged area according to the category of 'tone' described above.

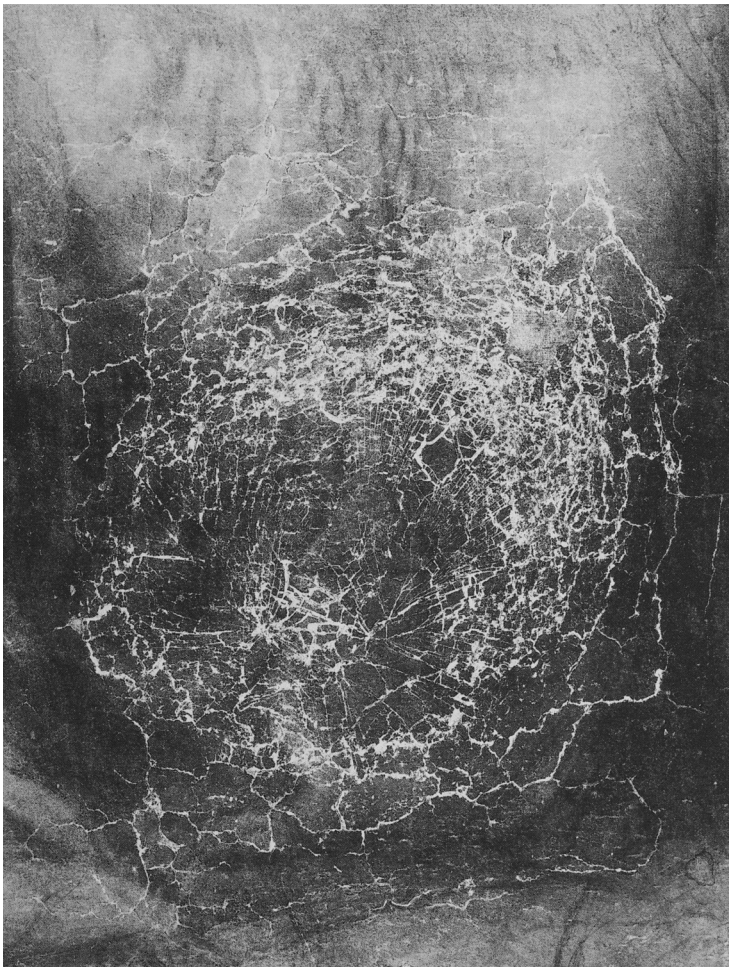

Figure 20
The damaged area after the fragments had been replaced, before retouching.

When all fragments had been returned to their positions, it was found that the total area of missing Cartoon amounted to approximately 1 cm^2 (Fig.20). This was replaced with matching tinted hand-made laid paper of the same period, type and weight as the original.

The shotgun damaged area of the Cartoon was now flat and with all fragments replaced but crazed as a result of the extensive paper fibre loss caused by the break-up of the surface. It was not possible to replace this loss with in-fills of matching paper pulp as tests proved that the refractive index of the pulp/adhesive mixture was quite different from that of the surrounding area and would have stood out in an obtrusive way from the original charcoal covered surface.

Restoration

Following a number of experiments with different media, a combination of finely powdered chalk and charcoal was found to be the most satisfactory from the point of view of refractive index. Application of the chalk and charcoal to the newly reformed surface was achieved using a fine sable brush and tiny spatula. In this way successive layers of pigment could be built up

between the valleys of each broken edge enabling full and sensitive control of tonality. Where necessary reversibility of the applied chalk and charcoal could be instantly carried out by sweeping the grooves using a small clean sable brush in combination with a vacuum suction tweezer unit. This was held 2–3 cm from the surface to avoid any resettling of unwanted in-fill dust on to the surrounding areas. By careful application of chalk and charcoal using the methods described above, it became possible to restore and tone in the damaged areas without the need to reconstruct or to interfere in any way with the original work.

Additional work on the Cartoon

It is known that the Cartoon has suffered over the centuries from poor repair work and restoration processes, many of which have changed in colour and form. For example, there are numerous areas of blackened lead white retouching which, due to atmospheric pollution, have changed chemically from white basic lead carbonate to black lead sulphide or, perhaps, lead dioxide. However, it was judged inadvisable to attempt to reverse these old changes for the present. In some cases old paper patches had begun to lift and separate, causing stresses and ultimately ruptures. These have all been newly repaired and made sound.

Many of the ridges and distortions visible in raking light (see Fig.10) were small areas of delamination. These were secured with thinned wheat starch adhesive, applied through the many fractures and ruptures in the surface of the Cartoon using a hypodermic syringe. Bonding was completed under gentle weighted pressure.

Acknowledgements

I wish to express my thanks to my colleague Anthony Reeve of the National Gallery Conservation Department for his help with the vacuum suction devices used in dealing with the damaged canvas on both the Cartoon and on test samples. Also to Raymond White, David Saunders and Aviva Burnstock for their kind cooperation, and finally to Martin Wyld, Chief Restorer, for his support and encouragement.

Materials and technique of the Leonardo Cartoon

Aviva Burnstock

This description of the materials used by Leonardo for *The Virgin and Child with S. Anne and S. John the Baptist* owes a great deal to an unpublished report made by Joyce Plesters, who examined the Cartoon when it was acquired by the Gallery in 1963. The recent damage to the Cartoon and subsequent need to propose a strategy for its restoration prompted a fuller investigation of the materials and technique of the drawing, with special attention to the disruption caused by the shotgun blast which affected the area of the Virgin's breast. A more detailed examination of the surface of the Cartoon than was done in the earlier study has been possible using the scanning electron microscope (SEM), which was acquired for the Scientific Department in 1985. The depth of field and clarity of the image obtained in the SEM have been useful in this case to reveal the drawing materials, their relationship to the paper fibres and the presence of tiny fragments of glass and other surface material.

The paper

Many fragments of paper became detached as a result of the shooting. A small piece from the damaged area was examined using the scanning electron microscope in order to identify the fibre type used. Fibres teased out from the edge of the paper were found to have the characteristic 'bamboo-like' structure of flax (Fig.21). This confirms that linen rag pulp was used to make the paper. No twisted cotton fibres could be seen in the sample, although cotton rags were also used for paper-making in Italy in Leonardo's time [1]. Cennino Cennini mentions a rag paper which is probably linen called '*carta bambagina*', which was one of the earliest papers to be used for drawing in Italy [2].

The Cartoon is made up of eight sheets of paper joined together, probably with animal glue. The paper is impregnated with animal glue and starch paste which causes the paper to appear yellowish in colour at the centre and on the reverse [3].

The impregnation of the paper with glue and its degree of degradation obscures the chain and laid lines which are present in all early hand-made papers. These lines correspond to the structure of the mould which is used in hand-made paper-making. The mould used to make the paper of the Cartoon is likely to have been constructed as a grid of vertically spaced metal 'chain' wires, typically one half inch to two inches apart and, horizontally, more closely spaced 'laid' wires. As the wet paper pulp drains and settles, an impression of the wire mould structure becomes part of the paper sheet as it forms. The laid and chain lines of papers in relatively good condition can be seen by transmitted light.

A beta-radiograph made of a fragment of the original paper from the edge of the Cartoon reveals the lines [4] (Fig.11). This technique enhances the contrast between areas of paper which differ in density or thickness, for example the variations caused by chain and laid lines. An

image of the lines is produced by sandwiching the paper between a source of beta-radiation and a piece of radiographic film. Differences in the thickness and density of the paper affect the passage of beta emissions (electrons) and, accordingly, contrast is produced on the film. The laid and chain lines can just be made out in the beta-radiograph of the sample from the Cartoon; however, the lines lack the sharpness and clarity of those in less degraded hand-made paper of similar composition and age (Fig.22).

A paper fragment from the damaged area was tested for acidity using a water immersion method [5]; the pH was found to be 3.3. High acidity in paper is indicative of the degree of degradation of the paper fibres, which manifests itself in brittleness and loss of strength. De-acidification of the original paper was considered in the conservation treatment plan (see the section above on restoration by Eric Harding).

The surface coating

The paper surface, where exposed, appears pinkish brown in colour. Examination of an unmounted fragment of paper from the turnover edge of the stretcher, which was of the same colour and general appearance as that in the central part of the Cartoon, was found to be coated with fine granular particles (Fig.23). The presence of the coating is illustrated most clearly by comparing this fragment with the uncoated surface of a similar kind of hand-made paper (Fig.24) where the flax fibres are exposed. The coating of the Cartoon was found to contain a mixture of red-brown iron oxide, a little carbon black and calcium sulphate. It is possible that the calcium sulphate in the mixture was originally calcium carbonate which has reacted with sulphur dioxide. It is more likely, considering the Italian origin of the Cartoon, that the white material used in the ground on the paper is gypsum (calcium sulphate). Gypsum bound in animal glue was used for the ground on Italian panels from the thirteenth century and was still the tradition at the beginning of the sixteenth century. The materials used for grounding panel paintings may have also been used for paper grounds.

The pigment of the brownish coating on the Cartoon does not appear to be bound in a medium and was probably rubbed dry into the paper as some form of chalk or pastel. There are descriptions of two methods used to prepare tinted papers from the fifteenth century. The dry method involved simply rubbing the powdered coating materials on to the paper surface by hand. Alternatively, the pigments were mixed with water and a little glue and applied using a broad brush or sponge [6]. A number of drawings by Leonardo survive which are on papers coated with various shades of red-brown, blue, cream and white. Vasari, in his descriptions of the drawing techniques of Florentine masters of the sixteenth century mentions the use of tinted paper for drawings of light and shade, in which the tint provides the mid-tone [7]. Papers coloured in the pulp stage, as opposed to coated papers, appeared for the first time in the last quarter of the fifteenth century and were manufactured in Venice [8].

The drawing materials

The original drawing is carried out in black with white heightening. The bold sweeping outlines of the figures are executed in charcoal, which was traditionally used for large-scale drawings and cartoons [9]. Charcoal can easily be brushed off and therefore is particularly suitable for working out large figure compositions and making adjustments in the planning stages of a major work.

Black splinter-like particles of variable size are visible at low magnification on the surface of a fragment of paper from the drapery at the Virgin's breast. The shape of these charcoal fragments is most clearly illustrated in the scanning electron microscope (Fig.25). Where most thickly applied, the charcoal lies on top of the brownish coating on the paper. No binding medium appears to be present. In other areas, the charcoal particles have been pressed into the coating, which consists of smaller rounded pigment particles (Fig.26).

Charcoal was prepared either by professional charcoal burners or by artists and their assistants [10]. Cennino describes the preparation of charcoal for drawing by sharpening and burning willow sticks in a closed vessel [11].

In addition to the free style of drawing in charcoal, the Cartoon contains passages of fine detailed work such as the hair of both child figures and the neckline of the Virgin's dress. These areas are drawn using a fine black line compared with the strokes made by the relatively coarse charcoal. Leonardo made several sketches in preparation for the composition. Three of these — the small much worked drawing of the Virgin and Child, S. Anne and S. John the Baptist [12] and two studies for the head of S. Anne [13] — appear to have been partly drawn using a material which is soft enough to produce a line much finer than would be produced by a stick of charcoal. When charcoal is sharpened to a fine point it becomes very brittle and produces a fragmentary line unlike those evident in the sketches. The fine lines have a glossy, reflective appearance which is more characteristic of graphite than the blue-black tint of charcoal. Graphite is a crystalline form of carbon which occurs as a natural mineral and was used for writing since ancient times, although there are few references to it in treatises on painting [14]. The hardness of graphite in its natural form depends on the percentage of clay associated with it. The hardest graphite contains the lowest percentage of clay.

Reference is made by Cennino Cennini to a stone from Piedmont which can be sharpened with a pen-knife and used for drawing [15]. It is described as being very black. This would suggest that it is not graphite, which usually has a greyish appearance. Black chalk, a natural mineral deposit of carbon-rich clay, may be the material described as the Piedmont stone. A 'chalk' of this kind with a high clay content and a soft form of graphite would handle similarly as a drawing material; either may have been used for the fine lines in the Cartoon and related studies.

Elemental analysis was carried out of a scraping of the black drawing material from the Cartoon and compared with a similar analysis of a reference standard of black chalk [16]. The sample from the Cartoon contained a

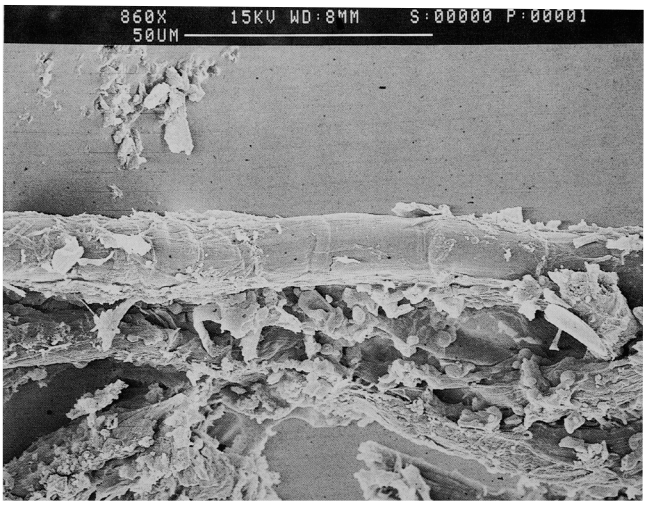

Figure 21 SEM micrograph of flax fibres from the paper of the *Cartoon*, showing characteristic structure. Gold-coated, 860×.

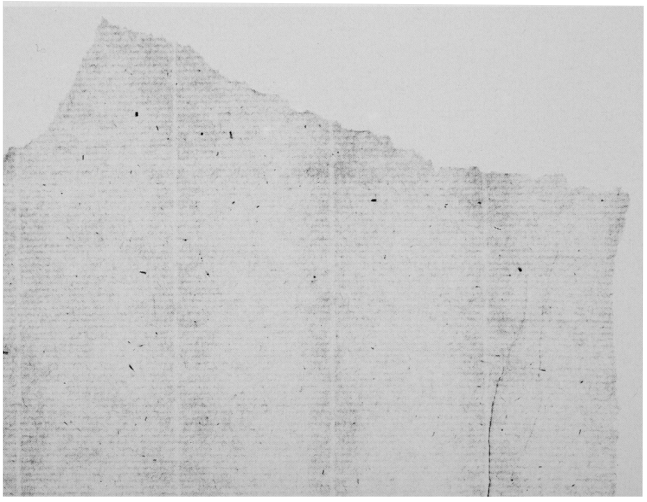

Figure 22 Paper of a similar type to that used for the Leonardo *Cartoon*, showing the chain and laid lines. Photographed in transmitted light, actual size.

Figure 23 SEM micrograph of the *Cartoon* paper surface showing fibres and ground. Gold-coated, 213×.

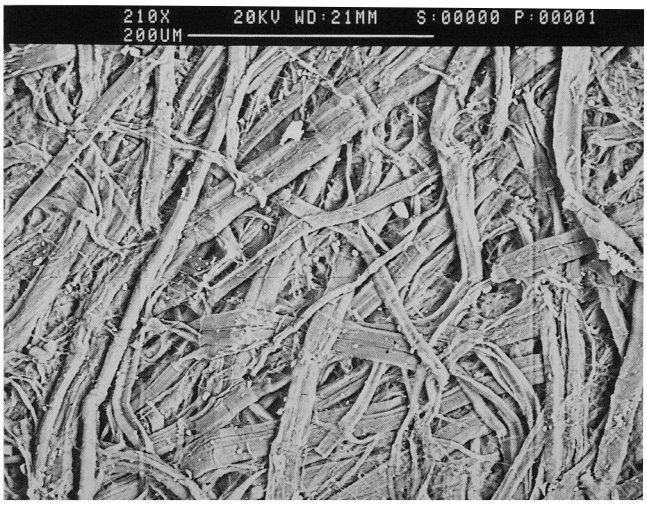

Figure 24 SEM micrograph of a similar paper to that of the *Cartoon* (see Fig.22). Gold-coated, 210×.

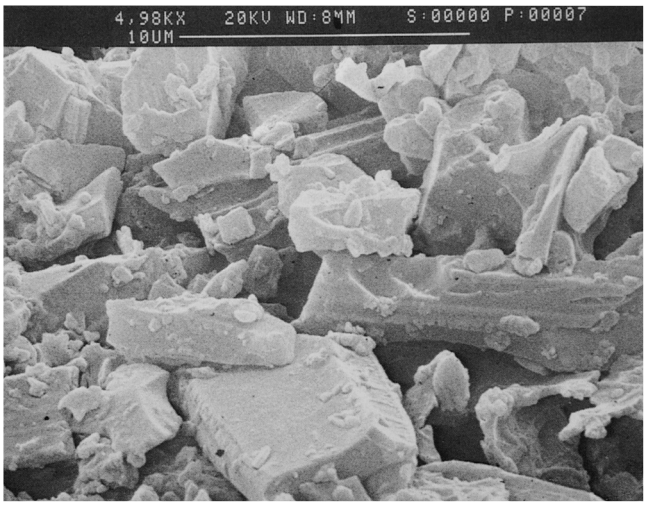

Figure 25 SEM micrograph of charcoal particles from original drawing of the Virgin's chest. Gold-coated, 4,980×.

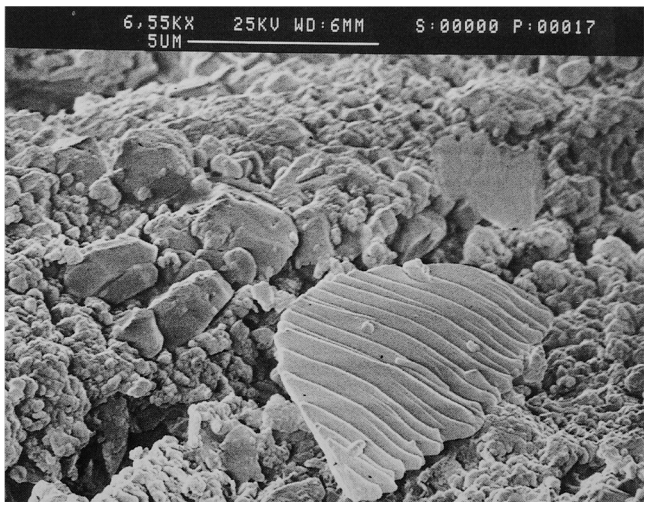

Figure 26 SEM micrograph of charcoal particles pressed into the ground on the Leonardo *Cartoon*. The large striated fragment is a sliver of glass from the shattered glazing. Gold-coated, 6,550×.

Figure 27 X-radiograph detail of the upper part of the *Cartoon* showing X-ray dense material in both original and retouched areas. The light areas show the presence of lead.

number of elements in addition to those found in the standard black chalk sample which suggests that some of the brownish ground layer had been scraped off with the drawing material. Unfortunately, black chalk contains no elements which positively distinguish it from the brown coating on the paper. This makes it difficult to identify with certainty using available analytical techniques.

The original white heightening in the Cartoon was found to be calcium sulphate. Sticks of gypsum and tailors' chalk are said to have been used for drawing [17]. Tailors' chalk consisted of talc or steatite, natural hydrous magnesium silicates. Magnesium was not detected in sufficient amounts on the Cartoon to suggest that tailors' chalk was used. High resolution microscopy using the SEM revealed no coccoliths which would indicate that natural chalk was originally present and subsequently converted to calcium sulphate. There is no mention in early writings on drawing materials of the use of pure calcium carbonate for the white areas. Pressed into a stick for use in drawing, natural chalk in its pure form may have been too hard to mark the paper.

The appearance of the white drawing material under the light microscope suggests that there is little or no binding medium associated with it. As is the case with the black drawing material, it is difficult to distinguish any binding medium from the various glues and sizes which have impregnated the paper.

A pinkish tinge observed in the flesh comes from the superimposition of white heightening over the pinkish brown preparation. Similarly, the bluish tints apparent in some places arise from scumbling a thin white layer over black. The bluish haze produced is sometimes known as the 'turbid medium effect'.

Strengthening of the highlights and retouching of damages in parts of the Cartoon have been done using lead white (basic lead carbonate). Areas where lead white has been applied can be seen in the X-radiograph (Fig.27). The X-ray absorbing lead white appears lightest on the radiograph over restorations to the paper support, most of which are along the upper edge. The highlights, particularly on the Virgin's face and neck, appear more diffuse in the radiograph. According to early treatises on technique, it was common practice to heighten the flesh tones and draperies by applying lead white thinly, possibly in a gum medium [18]. This would explain the difference between the unevenly applied lead white restorations and the smooth light veil of white of the Virgin's flesh apparent in the X-radiograph.

Several of the light areas on the radiograph appear brownish black on the surface of the Cartoon, which indicates that discoloration of the lead white has occurred. The most noticeable of these areas is in the centre of the Virgin's forehead, where the lead white retouching over a join has darkened, but not the lead white heightening of the flesh, which may or may not be an original part of the technique. A difference in binding medium may explain why the retouchings have discoloured and other areas have not changed.

It was not possible to identify the deterioration product of the lead white. However, there are two possible alternatives — lead sulphide and lead dioxide, both of which, due to their lead content, would appear light in the X-radiograph. White lead carbonate can be converted to black lead sulphide by the action of atmospheric sulphides [19]. This could have occurred at any time before the introduction of filtered air-conditioning in the Gallery which eliminates these pollutants. Alternatively, oxidation by micro-organisms of lead carbonate to brown lead dioxide may have caused the discoloration [20]. The paper, impregnated with glue and paste, is likely to be attractive to micro-organisms. Attempts to reverse the darkening of the patch in the top right-hand corner using oxidizing agents failed, which suggests that lead dioxide, rather than the sulphide is present.

The original pigments, carbon black, calcium sul-

phate, and brown iron oxide in the paper coating are all materials of great permanence. Carbon black does not change in appearance with varying conditions of acidity, light or atmospheric pollution. Calcium sulphate, unlike lead white, is not blackened by air-borne sulphides and is not affected by the acidity of the paper. Even if the original pigment had been calcium carbonate, its conversion to calcium sulphate would have little effect on the appearance of the Cartoon, as both are white solids similar in appearance and differ little in refractive index. Iron oxide pigments are similarly unaffected by light and atmosphere. In an acid medium in the presence of a little moisture, some iron may have been absorbed by the paper in the form of soluble iron salts. However, the pinkish brown pigment is still present on the paper surface, and little change can have taken place in its general appearance.

Some of the change in the appearance of the Cartoon is probably due to mechanical abrasion of the surface, causing smudging and losses. In addition, the presence of soot particles and general surface dirt may have produced a general greying and lowering of tone. The most significant cause of change in the appearance of the Cartoon is early conservation treatment, which resulted in tearing and wrinkling of the paper.

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3. Unpublished report by Joyce Plesters, 1963. Animal glue and starch were extracted from a piece of the original paper with hot water. Starch was identified using the iodine test (starch gives a characteristic blue-violet colour with iodine in alcohol or potassium iodide solution).
4. Beta-radiography was carried out by Mavis Bimson at the British Museum Research Laboratory.
5. A piece of original paper was soaked in water for one hour. The pH of the water was measured using BDH narrow range indicator paper with an accuracy of ± 0.2.
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14. There is a great deal of confusion in the literature about the use of graphite and black chalk. See Meder, J., *op.cit.*, pp.114–22; Thompson, D.V., *Materials of Medieval Painting*, Vol.2, Allen & Unwin (London 1936), p.88.
15. Thompson, D.V. (1960), *op.cit.*, p.20.
16. The reference sample of black chalk was supplied by Dr Maryan Ainsworth of the Metropolitan Museum, New York. EDX spectrum acquired from the reference sample contained the following elements in order of peak height: *Si*, *Al*, K, S, Ti, Fe. The sample of black drawing material contained the same elements with a higher proportion of iron and sulphur and a large calcium peak. This suggests the presence of coating material which contains gypsum and ferric oxide red pigment. A little lead was also present, which may indicate the presence of a small discoloured lead white retouching.
17. Thompson, D.V. (1960), *op.cit.*, p.104. Cennino mentions the use of tailors' chalk for drawing on dark coloured cloth in the preparation of wall hangings. Tailors' chalk was either gypsum (calcium sulphate), talc or steatite, natural hydrous magnesium silicates. See also Baldinucci, F., *Vocabolario Toscano dell'Arte del Disegno* [....] (Florence 1800), reprint of 1681 edition, p.65, which describes the use of a hard grey chalk and a semi-soft gypsum plaster for drawing.
18. See Maclehose, L., *op.cit.*, p.213; Thompson, D.V. (1960), *op.cit.*, p.16–18. See also Armenini, G.B., *On the true Precepts of the Art of Painting*, translated and edited by Edward J. Olszewski, from the original 1586 edition, Burt Franklin (1977), pp.126.
19. Plenderleith, H.J., *The Conservation of Antiquities and Works of Art*, Oxford University Press (Oxford 1956). Plate 12 shows a drawing in which lead white highlights have blackened. The blackening was reversed by treatment with hydrogen peroxide to convert the black lead sulphide to white lead sulphate.
20. Matteini, M. and Moles, A., 'The Reconversion of Oxidised White Lead in Mural Paintings: A Control after a Five Year Period', *Preprints, ICOM Committee for Conservation*, 6th triennial meeting, Ottawa (1981), 81/15/1. See also Petushkova, J.P. and Lyalikova, N.N., 'Microbiological Degradation of Lead Containing Pigments in Mural Paintings', *Studies in Conservation*, **31**, 2 (1986), pp. 66–8.

Plate 1 Leonardo da Vinci, *Cartoon: The Virgin and Child with S. Anne and S. John the Baptist* (No.6337), after repair and restoration.

Plate 4 (Right) Detail of the *Cartoon* after the fragments had been replaced in the area of damage, before retouching. The same stage is shown in Fig.20 (p.20).

Plate 2 (Below, left) The map used to record the positions of the fragments which were temporarily removed during repair.

Plate 3 (Below, right) Detail of the damaged area on the *Cartoon* after removal of glass and loose paper fragments, and after flattening of the canvas. The same stage is shown in Fig.17 (p.18).