Micro climates and moisture induced damage to paintings

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Abstract

Because of cold climates and minimal insulation in the walls of many buildings, the inside surfaces of exterior walls reach the dew point. Very high humidity levels and even condensation can occur on these surfaces. On hot summer days these same walls can reach elevated temperatures where the relative humidity near the interior surface can drop to as low as 30%. The zone close to such walls represents micro-climates that can differ widely from the intended "controlled" climates of museums and galleries. As a consequence, considerable damage to works of art can occur. This paper discusses some of the mechanisms that cause the damage to canvas paintings.

Micro climates near the interior surfaces of exterior walls

The most frequently encountered damage to paintings, both on canvas and on wood, results from exposure to high moisture levels. In both new and old historic buildings, moisture can condense on the inside of exterior walls from a variety of reasons. One of those reasons is the excessive humidification of the interior spaces of the building in the wintertime.

Figure 1 shows condensing water leaking from the exterior walls of the Smithsonian Institution's

Figure 1. Condensed water leaking from the joints in the wall of the Smithsonian Institution's Hirshhorn Museum and Sculpture Garden in the wintertime. (Photo by Gary Johannsen and Kevin Guifreda)

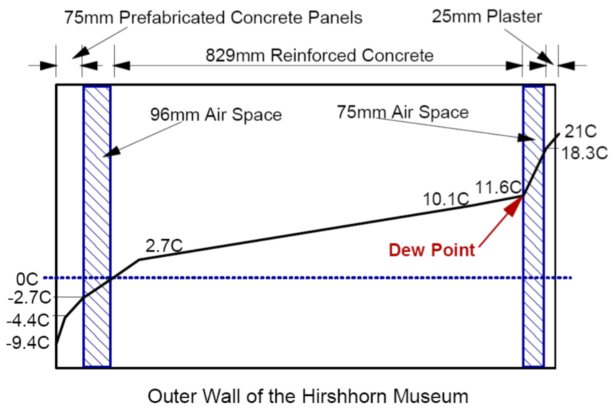

Figure 2. A computer generated temperature profile of an existing wall at the Hirshhorn Museum and Sculpture Garden. The inside surface is to the right. [1]

Hirshhorn Museum and Sculpture Garden. This water is a result of condensing humidified air within the walls on cold winter days. The Hirshhorn Museum and Sculpture Garden opened to the public on Oct. 4, 1974, so it is a relatively new building. Because of the architectural design of the building, the structural walls are massive. None the less, the walls get cold and the condensation occurs.

Figure 2 shows the temperature profile of an existing wall at the Hirshhorn Museum. The reinforced concrete structural wall is 892mm thick and where there are two air spaces, there is no insulation. On very cold winter days it can reach -10C outdoors where the interior environment of the building is 21C and 55% RH. While the temperature profile in Fig. 2 was generated by computer, actual measurements of select spaces verified that the outside, inside and inner wall temperatures are fairly accurate.

In the United States, many older buildings are constructed of brick masonry, no insulation, minimal air spaces, and highly decorative plaster interiors. These buildings are often converted for use as galleries and historic house museums. Some have been retrofitted with sophisticated heating, ventilation and air conditioning (HVAC) systems. In the winter time, the exterior walls of older buildings can get quite cold and the interior surfaces can reach the dew point because of elevated indoor RH levels.

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Figure 3. Condensed moisture running down the wall from behind one of several paintings at the Renwick Gallery of the Smithsonian Institution in Washington, D.C. (Photograph courtesy of Ehrenkrantz, Eckstut & Kuhn, Architects)

Figure 3 shows condensed water running down the interior face of an exterior wall from behind a painting at the Renwick Gallery of the Smithsonian Institution. The walls are 660 mm thick brick masonry walls having a 25 mm air space and a 25mm plaster finish. There is no insulation. The painting acted as insulation along the lower edge where there was contact with the wall. Moisture condensed at this lower edge. In this case the outdoor temperature was around -10°C and the temperature and relative humidity of the interior spaces was 21°C and 50%, with a dew point of 10°C .

In the summer time, the exterior walls get hot and the space behind the painting can be warmer than the interior of the exhibition gallery. If the outside wall surface temperature is 35°C (or hotter if in direct sunlight) there is a potential for the inside of the wall to reach a temperature of 28°C or more. In such cases the relative humidity behind the painting drops and can get as low as 33% or less. The microclimate behind paintings hanging on the inside of an exterior wall is entirely different from the "controlled climate" in the center of the gallery space. Behind paintings hanging on exterior walls it is entirely possible to have annual RH fluctuations from 30% to 100% while the center of the interior space is maintaining a constant 50% RH.

THE EFFECTS OF CYCLING RH ON CANVAS PAINTINGS

Canvas paintings represent some of the most complex structures in the cultural world. This is because of the widely varied materials used and their independent response to the environment. This can be illustrated by looking at each layer of a typical painting individually and then superimposing the

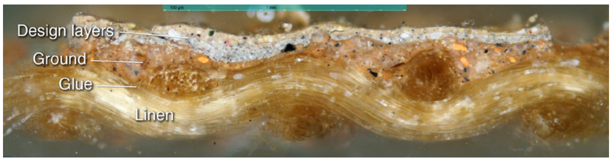

Figure 4. The construction of a traditional canvas supported painting. This assembly includes the "support" canvas, a glue size layer, an oil ground and the oil design layers. This particular section was from a 19th century Italian painting. The green bar at the top of the picture is 1mm . (The cross-section and photograph courtesy of Melvin J. Wachowiak)

layers together. A cross-section of a traditional 19th century Italian canvas supported oil painting is shown in Fig. 4. This assembly includes the "support" canvas, a glue size layer, an oil ground and the oil design layers. The glue size layer is almost too thin to see.

Figure 5 shows a detail of the same 19th century Italian painting but looking from the front. The glue size layer is an extremely thin film bridging the gaps in the weave of the canvas. Even though very thin, this layer is still very responsive to changes in RH.

It is commonly assumed that the canvas is the support of an old master painting but in fact the glue size provides support over most of the RH range. [2] This can be illustrated by looking at the individual layers of the painting when they are restrained and subjected to changes in relative humidity. While exploring each layer's response to environmental changes it is possible to determine the actual mechanisms that cause damage at different levels of relative humidity.

It is possible to measure the magnitude of forces in restrained linen samples as the RH changes. Note that the force per unit width acting on individual materials is used in this paper, since it is not

Figure 5. A detail of the same 19th century Italian painting shown in Fig. 4 but looking from the front. (Photograph courtesy of Melvin J. Wachowiak)

practical to calculate the stresses in textiles as force per unit area. Also, each of the materials examined will be of the thickness that might be encountered in typical easel paintings. Using this strategy, it is also possible to include the effects of the thicknesses of each of the different layers.

In building the composite painting up from the support canvas, it is useful to start with the canvas. The sample of linen tested was from an Ulster #8800 canvas. It is a medium weight canvas such as would be found on many easel paintings. Both the warp and weft directions were tested. An initial force was applied to the specimens at mid RH and the relative humidity was incrementally changed while the new level of force per width was recorded. As the relative humidity changed, so did the force acting on the canvas. This was continued for several cycles over a large range of relative humidity.

Figure 6 shows that between 10% RH and 60% RH there is relatively little change in the force on either the warp of fill directions of the textile. From 70% RH on there is a gradual increase in stress and above 80% RH the force increases dramatically. When damp or wet, loose textiles shrink dramatically and when restrained the shrinkage shows up as significant forces in the textile. This is the first indication that dramatic events take place in canvas paintings when the humidity gets very high. This behaviour was replicated using a wide variety of different textiles by Gerry Hedley at the Canadian Conservation Institute. [3]

Of all of the materials used in canvas paintings, hide glue is the strongest and nearly the stiffest. It is also the one material that develops the most force when restrained and desiccated. It is because this material is both stiff (and strong) and has a high dimensional response to humidity that it develops so much force. Figure 7 shows the force per width (stress) developed

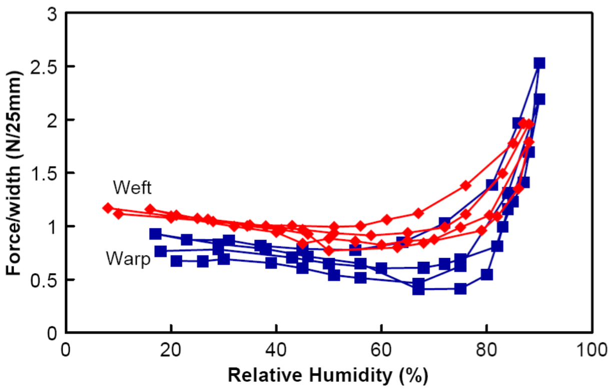

Figure 6. The tensile forces per width, measured in individual restrained samples of the #8800 linen in the warp and fill directions with changing relative humidity. The greatest forces develop when the relative humidity is above 75%.

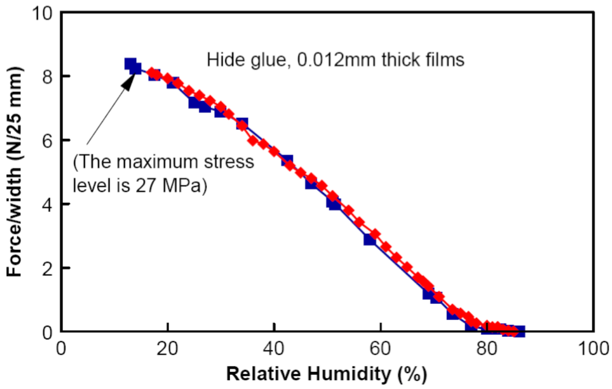

Figure 7. The force per width of restrained samples of hide glue when desiccated from 85% to 15% RH. The stress developed in the hide glue at the maximum force per width of these samples was 27 MPa.

in a very thin film of glue, 0.012mm, when it is restrained and desiccated from 85% to 15% RH. From 80% RH and above, the hide glue has no strength and therefore no ability to maintain the bond between the canvas and ground layers. The thickness of the film is about the same as that found as a size coating on paintings. (See Figures 4 and 5)

In general, the force per width developed in restrained and desiccated oil paint is considerably less than the force per width developed in other materials found in paintings. One of the reasons is that with the exception of some of the paints made with the earth colours, the dimensional response to humidity changes is low. While the earth colors tend to have a higher dimensional response, they have relatively low stiffness. Figure 8 shows two paint samples restrained and desiccated from around 75% to 5% RH. Even with this large change in relative humidity, the forces developed are low. So the likelihood that large excursions to low humidity can damage the oil paint layer is low. It takes a combination of

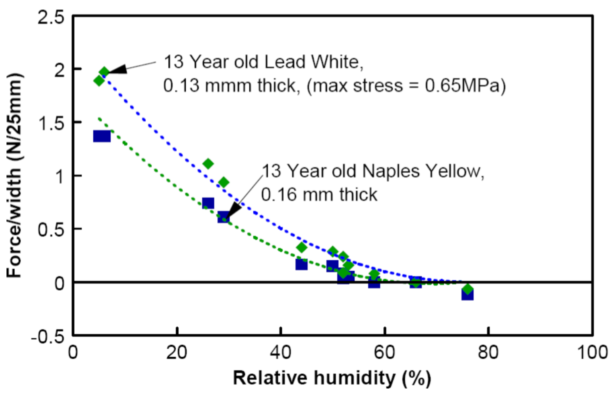

Figure 8. The force per width of restrained samples of lead white and Naples yellow oil paints. The stress of the white lead paint at the maximum force per width of this sample was only 0.65 MPa. The force per width of the paints is considerably lower than the hide glue and a bit higher than the #8800 linen shown in figure 6. The thicknesses indicated for the paint samples is typical of those found in paintings.

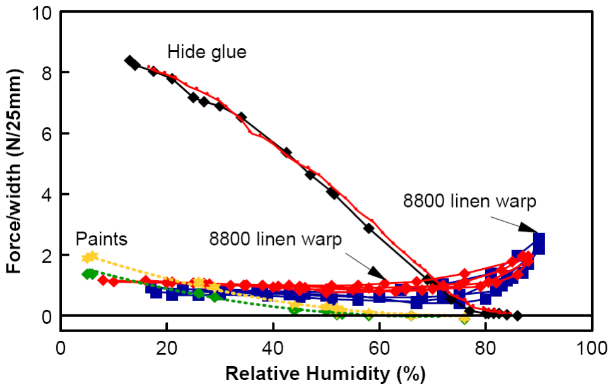

Figure 9. The force per width of restrained samples of linen, hide glue, and lead white and Naples yellow oil paints. The thickness of these films are as shown in their individual figures and would be typical of an oil painting painting. Using this figure it is possible to compare the responses of the individual layers to that of an actual canvas painting and to determine the different forces occurring at different levels of RH.

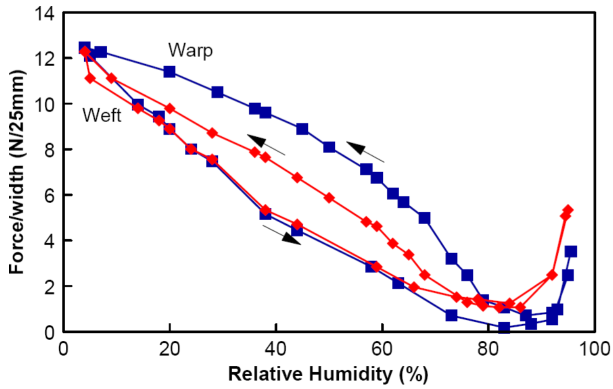

Figure 10. The forces per width of restrained samples of an unknown American portrait painted by Duncan Smith (1906), in both warp and weft directions. These painting samples were constructed with a medium weight machine woven fabric, a hide glue size, a lead white ground and a design layer of raw and burnt umber.

materials and their individual responses to changes in humidity to cause deterioration. This can be demonstrated by superimposing all of the layers of a painting together and comparing the results with an actual painting.

Superposition of the different layers of a painting

The information from Figs. 6, 7, and 8 is plotted on the same graph in Fig. 9. This makes it possible to compare the responses of the individual layers of a canvas painting to RH and to identify the RH levels that hold the most potential for damage. For example the fabric is developing high forces only at high RH levels and staying relatively constant at humidity levels below 80%. The hide glue is developing high forces at very low RH levels but loses all strength at levels above 80%RH. The paint films are developing relatively low forces and that is only at very low levels of RH.

The restrained testing of samples from actual paintings

Figure 10 shows the force per width developed in restrained samples of a 1906 painting by Duncan Smith. This painting was constructed with a medium weight, machine woven linen fabric, a hide glue size, a lead white ground and a design layer of raw and burnt umber. It is important to note that there are two areas of high force development, one at the very low levels of RH and the other at the very high levels of RH. This is consistent with the force development of hide glue and canvas as shown in Fig. 9. In the actual painting the fabric is developing high forces at high RH and the glue size is developing high forces at low RH.

Above 80% RH the hide glue is no longer acting as the secure bond between the ground and linen canvas. From 80% RH and above the paint layer is clearly at risk of delaminating from the canvas. At this same RH the paints films are the most flexible but are also in their weakest state. Above 80% RH, the fabric will shrink if loose and certainly could cause delamination of the design layers attached to it. One further comment here is that from 10% RH to 75% RH, the force level in the glue layer is much higher than in the other layers, including the linen canvas. In this range it is the hide glue that is supporting the painting, not the canvas.

Not all linens show the same behaviour. Some linens are woven such that the weft direction yarns are quite straight and have little crimp. It is the crimp in a yarn that causes high humidity shrinkage when loose and high forces when restrained. Also low quality linens can be used for commercially prepared artists' canvases. In order to get a stiffer feel for the linen, heavier layers of glue size are applied before the oil ground is applied. This results in even higher forces in the low humidity ranges.

Effects of cycling canvas paintings over large ranges of relative humidity

If a canvas painting is exposed to large cyclic changes in relative humidity, a pattern of corner cracks can occur. This can be demonstrated by constructing a "mock" painting of canvas, a size layer of hide glue and a "design layer" composed of a hard gesso film having the mechanical properties of an old brittle oil paint film. The dimensions of the painting were 505mm x 762mm. The gesso layer was a hide glue and calcium carbonate mixture. [4]

Figure 11 illustrates the results of such an experiment. This mock painting was cycled from 90% RH to 35% RH and then back to 90% RH. Each half cycle (from high to low RH or low to high RH) required just less than 24 hours for full equilibration. Periodically, the test painting was examined to see what cracking might have occurred. It was observed that with one small exception, all of the cracks occurred at the corners of the painting. At the ends of selected cycles (#4, #7, and #9), the ends of the cracks were marked.

After nine full cycles the crack extension ceased, as was confirmed by additional cycles. The painting was then subjected to several more severe cycles from 95% RH to 20%RH and back. There was no additional cracking or crack extension. What is of interest is that the first 4 cycles caused the most damage and subsequent cycles only produced smaller increments of crack extension until it ceased altogether. More severe RH cycles did not add to the damage. The cracks that did occur began to act as expansion joints and now the painting can experience large RH cycling without further damage.

From the discussion above, hide glue loses strength at high humidity levels but develops very high stresses when desiccated. It was also shown that, acting alone, paint layers won't generally develop high stresses and damage themselves when restrained and desiccated. It is the desiccation of

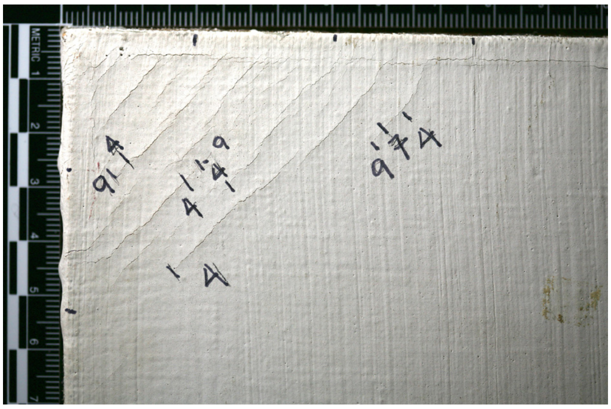

Figure 11. The results of cycling an experimental "mock" painting to cycles of large changes in relative humidity. The cycle range was from 90% RH to 35% RH. The crack limits at 4, 7 and 9 cycles are marked. Additional cycling of a greater RH range beyond the initial nine cycles did no further damage, because the cracks relieved the stresses caused by further RH cycles. This model painting was constructed with a stretched canvas, a hide glue size and a stiff gesso acting as a design layer.

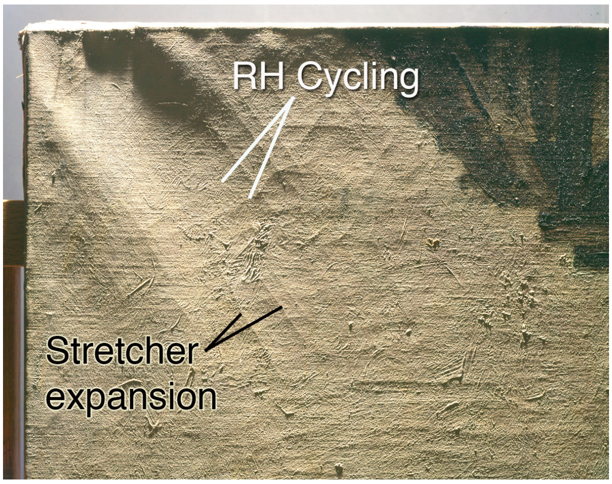

Figure 12. The combination of crack patterns from stretcher expansion and RH cycling over a large range.

the glue layer acting on the paint layer that causes damage. The cracks shown in the corner of the test painting (Fig 11) reflect the effects of the hide glue (and to a small extent the paint itself) pulling from the central regions and away from the corners of the painting. This distorts the design layers sufficiently to cause cracking in the paint layer at the corners.

In an actual painting, it is not unusual to see both the cracking from stretcher expansion and environmental cycling in large ranges of relative humidity combined. This is illustrated in Fig. 12. [5]

Condensed moisture damage to canvas paintings

One of the most frequently encountered types of damage to paintings, both on canvas and on wood is a result of exposure to high moisture levels. In old historic buildings, the moisture can condense on the inside of exterior walls from a variety of reasons. One reason has already been explained. Another reason that condensation can occur is that in old stone buildings, the masonry walls are cooled during the wintertime. These massive stone walls, due to their high thermal mass, are slow to warm up with the changing seasons and in the spring time warm moist air enters the building along with visitors through open doors. This results in extensive condensation on not only the walls but on paintings hanging on those walls. This occurs on many of the monuments such as the Lincoln and Jefferson Memorials in Washington, D.C. in the United States.

Water condensing on paintings often tends to run to the bottom of the painting and typically causes damage as shown in Fig. 13. In this case there

Figure 13. A detail of a 19th century Italian painting. It is clear that total separation of the paint and ground layers from the canvas has occurred. The amount of moisture was sufficient to cause cracking of the design layers and failure of the bond at the glue layer. The canvas shrank, and the paint cleaved from the canvas. (Photo by Matteo Rossi Doria)

was sufficient water on the canvas that it totally disrupted the adhesive bond of the animal glue size layer. Hence the canvas shrank, glue size lost all of it adhesive strength and the paint and ground layers completely detached from the canvas. Now there is insufficient room to fit the broken pieces of the paint back into proper alignment.

Selectivity in RH Damage

The chemistry of oil paint is very complex and, understandably, properties of dry films vary with the pigment. For example, paints made with basic lead carbonate dry to tough durable films while those made with the earth colors form weak films. [6 7] The mechanical properties of several different paints are illustrated in Fig 14. One would expect that the white lead paint, because of its strength and low dimensional response to moisture would survive large swings in relative humidity. On the other hand one might suspect that weak and dimensionally responsive paints like umber, ocher, and Sienna would most likely suffer considerable damage in the same harsh environment. [8]

At high moisture levels the earth colours have very little strength and the hide glue size has none. Therefore neither has the ability to resist damage. Failure is going to be preferentially in the earth colours. Figure 15 illustrates selective damage to a 19th century Italian painting. Here the white lead paints are relatively intact while the earth colours are seriously damaged. Clearly avoiding high humidity levels is of primary importance. Moisture induced damage to paintings is selective in that the weaker paints will fail and the durable ones will maintain some stability.

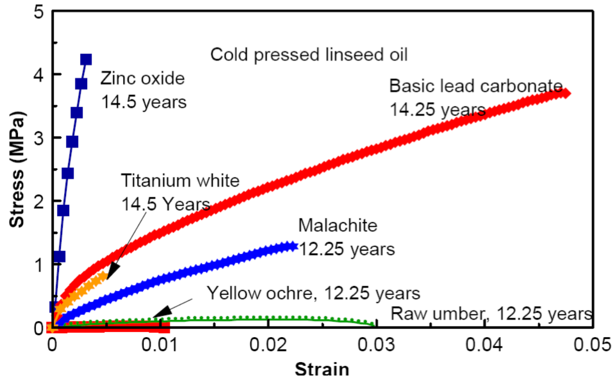

Figure 14. The results of stress-strain tests conducted on paints made with different pigments. The various pigments have a dramatic effect on the mechanical properties of oil paints.

This is in contrast to damage due to excessively low temperatures which has the same adverse effects on all paints. [4, 5]

Conclusions

While it is possible to show that low relative humidity excursions can cause damage, the most serious RH related damage to paintings is generally a result of very high moisture levels. While the source of the moisture can be leaking roofs or damp basements, a common cause of damage is high humidity and condensation on the inside surface of cold exterior walls. Lowering the indoor relative humidity and keeping an air space between the works of art and the wall can go a long way in minimizing damage. [9]

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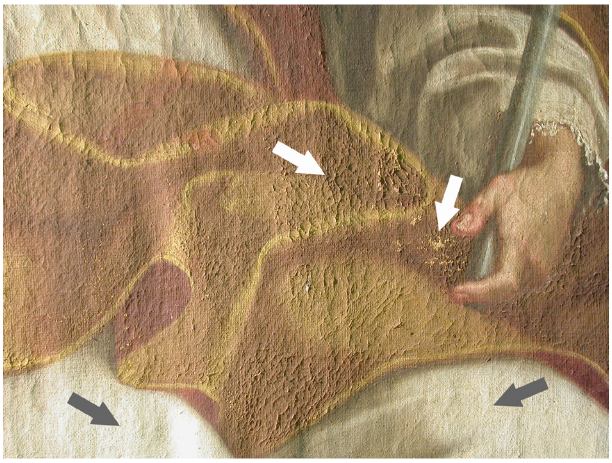

Figure 15. A detail of a painting containing both white lead paints (blue arrows) and paints made with the earth colours, ochre and sienna (red arrows). This painting was damaged by wet walls. (Photo by Matteo Rossi Doria).

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