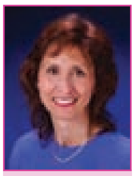


M. Sue Benford

**M. SUE BENFORD**
**JOSEPH G. MARINO**

# Role of calcium carbonate in fibre discoloration on the Shroud of Turin

**ABSTRACT**

*Introduction: The Shroud of Turin, a linen cloth bearing the faint, yellowed image of an apparently-crucified man, is the most intensely studied artifact of all time. Scientific tests revealed that the image color resides on the topmost fibers at the highest parts of the weave resulting from a chemical surface change in the linen. We propose and preliminarily test a novel hypothesis that precipitated calcium carbonate crystal, originating from a natural fabric washing process, played a significant role in the starch surface discoloration.*
*Methods and materials: Modern, dye-free linen was supersaturated in hard tap water with mild acetic acid and air dried. Resulting discolored fibers were scientifically evaluated in comparison to pristine fibers and Shroud image fibers.*
*Results: Evaluations using scanning electron microscope, Micro- Attenuated Total Internal Reflectance Fourier-transform infrared analysis (ATR-FTIR), secondary ion mass spectrometry, chemical analyses, and microscopic comparative analyses all revealed nearly identical findings as those found on Shroud image fibers.*
*Discussion: To date, all Shroud image-formation hypotheses have failed when compared with known data. We present preliminary experimental data supporting the novel hypothesis that precipitated calcium carbonate played a significant role in differentially discoloring the surface fibers in the image region of the Shroud. Our hypothesis may also explain the Shroud image intensity as related to cloth-body distance studies.*
*Conclusion: Although the results of this study are compelling, several other experiments need to be conducted including those that incorporate the parameters occurring in a Jerusalem tomb microenvironment. The success of this hypothesis does not speak to the issue of whose body was wrapped in the Shroud or the time period of image formation.*

## INTRODUCTION

The Shroud of Turin, the enigmatic, linen cloth bearing the faint, yellowed image of an apparently-crucified man, is the most intensely studied artifact of all time. Science and religion have spent untold hours on the cloth, believed to be the actual burial cloth of Jesus of Nazareth. Although most of the data gathered after a five-day study of the cloth in 1978 by a team known as the Shroud of Turin Research Group (STURP) pointed toward authenticity, a 1988 carbon-14 dating (C-14) test produced results of AD 1260-1390, which was too late for Jesus' time frame of circa AD 30. However, recent research has called into question the 1988 results (1), thus reopening the question of the Shroud's provenance as a 1st century burial cloth bearing the image of a crucified Jewish man.

Attempts to explain the image-formation process have involved the use of numerous scientific tests including microscopy, visible and ultraviolet spectrometry, infrared spectrometry, x-ray fluorescence spectrometry, thermography, microchemistry, petrographic microscopy, scanning-electron microscopy, energy -dispersive x-ray analysis, pyrolysis-mass-spectrometry, and laser-microprobe Raman analyses among others. In summary, the tests revealed that the image color exclusively resides on the topmost fibers at the highest parts of the weave, and the cellulose was not involved in color production. The colored layer is 200-600 nanometers thick, yellow to brown in color, and contains no protein, painting medium or protein-containing coating. Microchemical tests with iodine detected the presence of starch impurities on the surfaces of linen fibers from the Shroud (2). Further, two STURP team members reported that: "The absence of products expected from a high-temperature cellulose degradation […] suggests that the process that formed the final chemistry took place at lower temperatures (less than 200°C), because no pyrolytic compounds were found" (3).

In addition to these findings, another of the verified characteristics confirmed about the Shroud of Turin is the presence of large (~1 wt percent) amounts of calcium on the cloth. A new observation of significance related to the Shroud's calcium is its distribution in relationship to the image. Data from the measurements taken in 1978 reveal a distinct inequality in the surface calcium distribution on the cloth. The average aerial calcium density for Shroud image areas is 209 $mg/cm^2$ while the pristine/non-image area is almost half as much at 116 $mg/cm^2$. The patch area, applied during repairs made in 1534 AD, falls closer to the pristine area at 160 $mg/cm^2$ (4). The calcium is most likely underestimated in these results because no account was taken of its distribution within the cloth. "X-ray attenuation by hydrocarbons is greatest at lower energies and in these measurements would strongly suppress the calcium peak. If the calcium were distributed uniformly through the cloth instead of at the surface, the actual weight concentrations could be twice as large as the numbers quoted" (5). Thus, these measurements only represent the surface calcium deposits and not the calcium within the linen fibers and surface surfactant.

If the Shroud of Turin is of 1st century origin, it would have been subject to ancient linen "manufacturing" processes including having been washed in *Saponaria officinalis*. After being washed these fabrics were "laid out on bushes to dry" causing materials in the wash water, such as calcium carbonate and iron, to concentrate at the drying surface (6). Rogers and Arnoldi (2003) postulated a natural image-formation hypothesis that suggested impurities in ancient linen were

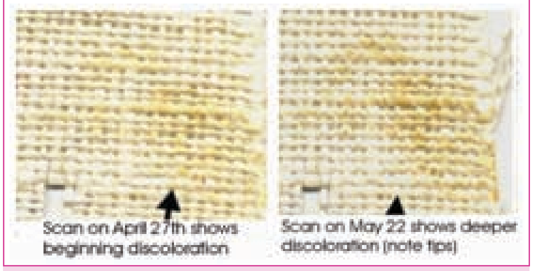



Figure 1.

suspended by the surfactant property of a *Saponaria officinalis* washing solution and were ultimately concentrated at the cloth surface via evaporation. Historically, linen makers avoided ferruginous waters for retting as it stains the cloth. Like iron, calcium will also stain cloth in a similar manner (7).

During the 1980's, a series of image-formation tests were conducted, by a team led by archaeologist Dr. Eugenia Nitowski, aimed at reproducing the post-crucifixion tomb setting that may have been present during 1st century Jerusalem. Nitowski used water-filled manikins (temp. between 110 and 115 degrees F, 43 – 46 C) to duplicate reported temperatures of post-mortem body heat from severely traumatized victims. Blood and "sweat" composed of normal saline (9 percent) and acetic acid was added to reproduce the acidic condition of blood and perspiration in trauma and death. The prepared manikin was then placed in untreated, modern Belgian linen that had been lightly dusted with calcium carbonate/calcite ($CaCO_3$). Nitowski hypothesized that surface calcite from the limestone tomb had reacted with the post-mortem corpse to discolor the linen. She posited that the acetic acid and calcite set-up conditions for an acid-alkaline reaction that would be further accelerated by corpse heat.

During the first test, the shrouded manikin was placed in a totally dark basement with environmental temperatures ranging from 62 – 65 degrees F and relative humidity from 58 – 66 percent. Both the manikin and cloth were sprayed with a water mist to replicate a damp limestone tomb characteristic of those found in Jerusalem. The apparatus was left for 30.5 hours at which time the cloth was examined for an image. An image was obtained in the areas of the manikin's body that retained heat the longest (chest and back). The image was described as darker and more clearly defined on the outside of the cloth. Microscope examination of individual discolored threads showed both yellowed and colorless fibers, which indicated an uneven penetration. Additional experiments were conducted with variable conditions applied. In summary, Nitowski and her team formed several conclusions that pointed to a mixture of conditions having been required to produce an image on the linen shroud. These conditions and parameters included body heat from the corpse, acidic fluids, cave/tomb microenvironmental conditions, linen characteristics, and calcium carbonate.

Nitowski's images were independently evaluated by the late STURP chemist Dr. Alan Adler. Adler reported: "The images are very faint, however, they may become more distinct with time as more oxidation ensues. Like the material I studied from the Shroud of Turin, both image and non-image fibrils give positive tests for Fe, Ca, aldehyde, and cellulose carboxyl groups […] the Ca tests are very markedly different between image and non-image" (8). Adler's observations that the manikin's image area, like the Shroud's, contains disproportionately higher calcium than non-image areas, suggests a possible role of calcium in the image formation process. This is especially pertinent considering Nitowski dusted her entire cloth with calcium, suggesting that some process besides the added surface contamination differentially influenced observable calcium content in image versus non-image areas.

As such, we propose a testable alternate hypothesis in reference to the formation of the image on the Shroud of Turin. We posit that at least a portion of the surface calcium observed in the Shroud image area may have precipitated from the cloth disproportionately in the image areas based upon uneven heat dissipation from the post-mortem corpse. Further, we posit that the precipitated calcium carbonate (calcite) crystals, originating from a natural fabric washing process, played a significant role in the yellow-brown starch surface discoloration, which ultimately formed the image. Our hypothesis may also explain the Shroud image intensity as related to cloth-body distance studies. In this paper we will demonstrate how this process was driven by the microenvironmental conditions of the tomb, the post-mortem corpse conditions, and ancient linen material and manufacture. We further demonstrate and explain how this resultant image appeared over time.

## MATERIALS AND METHODS

In order to test the above hypothesis we secured a 1:1 tabby woven piece of linen provided by Dr. Alan Adler, who described the sample as modern but "free of dyes and starches". The cloth was uniformly white in color without any notable discolorations. The sample was supersaturated by boiling in hard tap water (naturally containing calcium and magnesium) and white vinegar for fifteen minutes. The distilled white vinegar contains 5 percent acetic acid and has a pH of ~2.4. Weak acids such as acetic acid will react with calcite. Additionally, decreasing the pH in the water increases the maximum calcium concentration.

A sub-sample measuring 4 x 2.5 cm was cut from the Adler linen and became the experimental sample. The wet sub-sample was placed in a four-sided, 6" tall cardboard "tomb" and placed in a darkened closet with ambient temperature ranging from 68 – 72 degrees F, humidity ranging from 54 – 60 percent and no perceptible air current. The sub-sample was left in the dark for seven days (March 15 – March 22) undisturbed. This time period was arbitrary and most likely insignificant to the ultimate outcome. The sample was handled with bare hands and did not come into contact with the cardboard structure. No external electromagnetic or other heat or energy sources were near the structure during the experiment.

## RESULTS

Upon removing the linen from the designated "tomb," an initial visual examination revealed three areas of faint, yellow discoloration, on one side only, which were barely visible to the naked eye. No other distinctive marks were observable until approximately one month after the end of the experiment (April 27), at which time a larger, clearly discernible light-yellow "fingerprint" discoloration became apparent on the opposite side of the sub-sample. The discolored area deepened in hue over the course of approximately one more month (May 22), at which time the color fixated (see Figure 1).

Scanning electron microscopy (SEM) (JEOL, Model JSM 820, chemical analyses with EDS) was employed to examine the chemical and microscopic properties of the discolored and pristine regions of the


Figure 2. SEM analysis revealed both calcium and magnesium in discolored regions of experimental sub-sample.

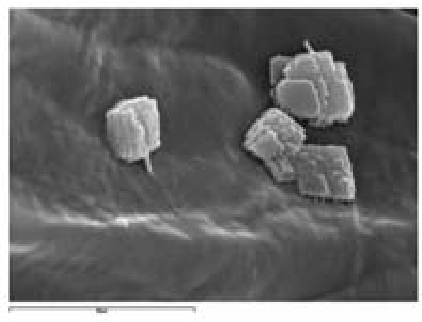
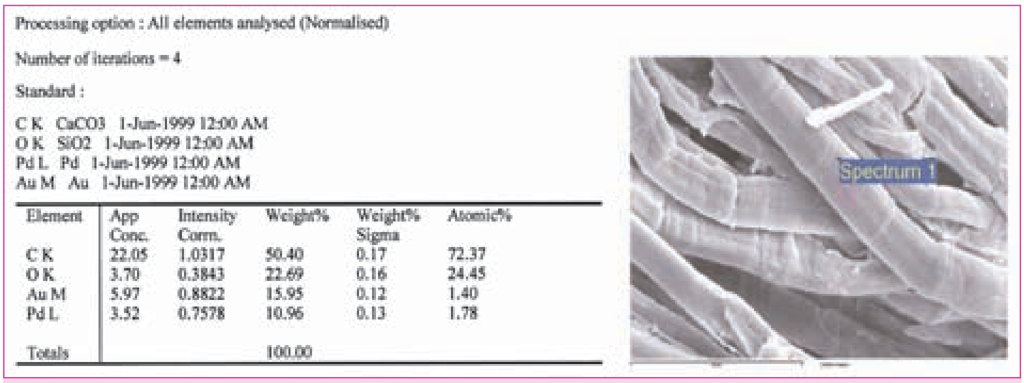


Figure 3. Rhombohedral calcite as seen growing from the discolored regions of the experimental sub-sample.



Processing option : All elements analysed (Normalised)

Number of iterations = 4

Standard :

C K CaCO3 1-Jun-1999 12:00 AM
O K SiO2 1-Jun-1999 12:00 AM
Pd L Pd 1-Jun-1999 12:00 AM
Au M Au 1-Jun-1999 12:00 AM

| Element | App Conc. | Intensity Corrn. | Weight% | Weight% Sigma | Atomic% |
|---|---|---|---|---|---|
| C K | 22.05 | 1.0317 | 50.40 | 0.17 | 72.37 |
| O K | 3.70 | 0.3843 | 22.69 | 0.16 | 24.45 |
| Au M | 5.97 | 0.8822 | 15.95 | 0.12 | 1.40 |
| Pd L | 3.52 | 0.7578 | 10.96 | 0.13 | 1.78 |
| Totals | | | 100.00 | | |



Figure 4. As depicted here, all pristine regions of experimental sub-sample were free of calcium.

sub-sample. These tests were conducted at The Ohio State University's (OSU) Microscopic and Chemical Analysis Research Center (MARC Lab). Samples from discolored and pristine fibers were prepared with gold coating using DESK II (Denton vacuum). Images were taken with WILD photoautomat MPS 55, WILD M3 stereomicroscope and using Kodak elite chrome 160T. The most notable difference found between the two regions was in the high proportion of calcium identified only in the discolored areas (Figs 2 and 3). Magnesium was also identified on several of the discolored-region fibers (Figure 2). No calcium or magnesium were seen in any of the multiple pristine region scans at any magnification (see Figure 4)

In every scan where discoloration was observed, what appeared to be crystalline calcium deposits also were present. In several instances, the crystals contained stalks attached to the fiber surface. Subsequent evaluation of the calcium crystals by the OSU Geology department revealed that the crystals were calcite (calcium carbonate) and, predominately, 5-10 micron-sized rhombohedrals (see Figure 3).

Follow-up comparative testing was conducted at the Molecular Microspectroscopy Laboratory of the Department of Chemistry & Biochemistry at Miami (OH) University using Micro-Attenuated Total Internal Reflectance Fourier-transform infrared analysis (ATR-FTIR) (see Figure 5). Notable differences between the discolored and pristine spectra were found in both the 3300 and 1100 $cm^{-1}$ regions. These findings suggest a dehydration effect involving the discolored fibers.

| Full Width Half Mass | Pristine fiber surface | Discolored fiber surface |
|---|---|---|
| Carbon | 2.00 | 1.90 |
| Oxygen | 3.70 | 2.00 |
| Nitrogen | 3.20 | 3.10 |

Table 1. SIMS analysis of experimental sub-sample showing loss of oxygen in discolored region.

Additional evaluation of the discolored versus pristine regions of the sub-sample was done at OSU using secondary ion mass spectrometry (SIMS) to analyze the percentage of carbon, oxygen and nitrogen elemental compositions of the surface of the fibers. The results revealed a nearly two-fold loss of oxygen from the discolored fiber surface supporting the hypothesis that dehydration occurred in the discolored region (see Table 1).

The sub-sample was sent to the late Los Alamos National Labs (LANL) and former-STURP chemist, Ray Rogers, for evaluation in direct comparison with Shroud image fibers, which were in Rogers' possession. Rogers was blinded to the source of the linen as well as to the experimental protocol.

Rogers' analysis identified the following characteristics of the sub-sample:

- The color distribution in the discolored area looks very much like the surface of the Shroud.
- The color is discontinuous and only on the topmost 1 or 2 fibers.
- The color does not penetrate the threads.
- The color matches the color on the Shroud image fibers.
- The discolored region does not fluoresce: matching the Shroud.
- At 25X magnification in oblique light and using a petrographic microscope, the discolored region looks nearly identical to the Shroud's image area.
- At 100X, the discolored region looks superficially slightly different. The color appears in discrete zones.
- There are places where the color descends and ends abruptly on several fibrils simultaneously on a thread that is going under an adjoining thread.
- When the discolored fibrils are mounted in 1.515 immersion oil, the color is a close match for the Shroud.
- Identical with the Shroud, there is essentially no color in the medullas.
- The color does not affect the index of refraction, which means it is an extremely thin layer in the discolored zones. This is also characteristic of the Shroud.
- In several instances, the color shows up on only one side of a fibril. This further demonstrates the extreme surface nature of the discoloration.
- The depth of the color (ranging from light yellow to brownish) depends on local concentrations of the surface sizing.
- The color ends abruptly in some places where the sizing ends or abruptly changes thickness to a much thinner film. However, the sizing is still seen in uncolored parts of the samples. This means that something differentially affected the colored areas of the linen even though the sizing is all over the surface of the linen.
- The Shroud color is a result of a surface dehydrated polysaccharide, suggesting something was there and was differentially affected as in the experimental sample.
- In conclusion, whatever energy impacted the discolored regions of the cloth was enough to dehydrate the sizing material but not enough to affect the cellulose. This is true also for the Shroud.

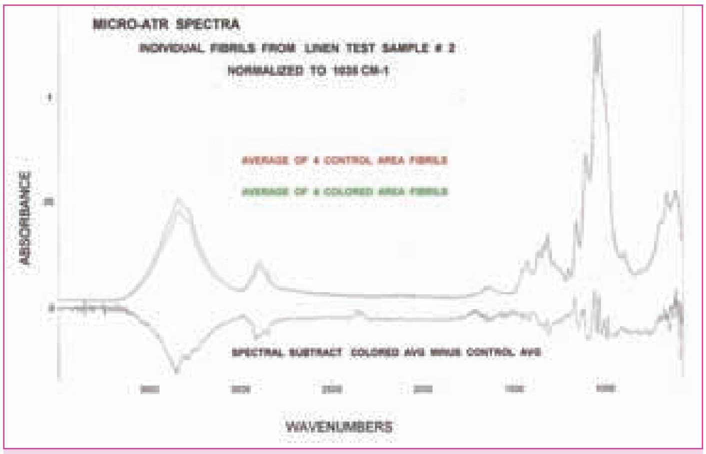



Figure 5. Micro-ATR-FTIR of sub-sample indicated dehydration in discolored regions similar to Shroud image fibers.

The following microphotographs (Figs. 6-10) were produced by Ray Rogers as part of his analysis.
Rogers also noted that "all visible surface contaminants (gum-like encrustations) were removed in HCl, but the colors remained […] It appears that the colors are pH-sensitive forms of the fabric brighteners or dyes made from them by the image production process" (9).

Figure 6. Left: Macro photograph of discolored sub-sample. Right: Microphotograph of Shroud image discoloration, Copyright © 1978 Mark Evans.

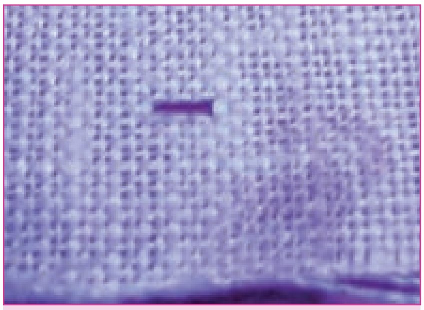


Figure 7. UV photograph showing lack of fluorescence in discolored region.

**DISCUSSION**

Comprehensive and rigorous scientific studies conducted on the Shroud of Turin image by STURP researchers in 1978, and most recently updated by Ray Rogers, concluded that the image appearing on the Shroud was the result of a chemical surface change in the linen due to disproportionately-occurring, dehydrative acid oxidation of the surface starch layer on the cellulose fibers (see 1-3). Numerous hypotheses have been posited suggesting viable mechanisms to explain the faint image of an apparent crucifixion victim on the Shroud of Turin. To date, all have failed when compared with actual observations and known data pertaining to the Shroud. Significantly, none of them has satisfactorily produced experimental evidence matching the superficial discoloration of the surface starch layer on the image fibers. Previously published studies on contact and material-transfer methods (10) eliminated hypotheses based solely on vapor-diffusion and/or material-transfer mechanisms. Additionally, hot irons, statues, ionizing radiation, and coronal discharge, which are the most prevalent hypotheses, must also be ruled out, because the chemical and physical by-products are significantly different than those found on the Shroud. These image-formation hypotheses are further eliminated by their inability to explain and/or reproduce the distinct half-tone, vertical-relief pattern variations seen on the Shroud.

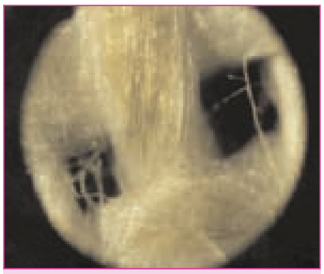


Figure 8. Oblique light, 100X, dry. Shows spots of deeper color and distribution of color on individual fibrils.

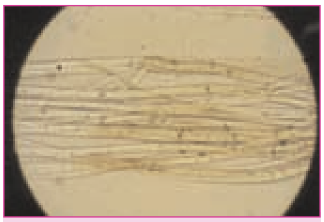


Figure 9. Example of how the color ends abruptly with an increase in optical density on some fibrils. One vertical end just above the main smudge at the center is heavily coated and colored.

Recent research has provided compelling data that the Shroud may be older than the medieval date obtained by the 1988 Carbon-14 test, which possibly incorporated a repaired section of the cloth (11). As such, consideration of image formation hypotheses, such as the one proposed in this paper, which employ scenarios existing within an ancient Jerusalem tomb are warranted.
In this paper, we present preliminary experimental data supporting the hypothesis that precipitated calcium carbonate (calcite) played a significant role in differentially discoloring the surface fibers in the image region of the Shroud. Calcium carbonate is an abundant mineral comprising approximately 4 percent of the earth's crust. Many studies have described both the natural and the synthetic precipitation of the various forms of calcite. The conditions under which precipitation occurs, including the importance of initial supersaturation, temperature, pH, hydrodynamics and the presence of impurities and additives, are well known (12). As revealed in our experiment, not only was the surface layer of the sub-sample macroscopically discolored matching the Shroud image fibers, but the microscopic and chemical comparisons are strikingly similar as well.
If the Shroud was of 1st century middle-eastern origin, it would have been soaked in waters containing high levels of calcite, supersaturating the cloth fibers and the outer starch layer typical of ancient linen textiles processed using *Saponaria officinalis*. X-ray studies confirm high levels of calcium in the cloth, thus supporting this assertion. Damp Jerusalem cave-like tombs provided a suitable microenvironment conducive to calcite growth and precipitation from supersaturated materials. Calcium carbonate precipitating out of supersaturated solutions is known to form micron-sized rhombohedral calcite crystals on the air-water interface (13).

Figure 10. Shows colored encrustation in 1.515 oil at 400X. There is no surface decrepitation associated with the color.

For samples heated to the proposed corpse temperature of approximately 40 to 45°C the crystal sizes range from 5 to 30 microns. This is the approximate size of a rhombohedral calcite crystal found to be growing on a Shroud blood-containing fiber that was in a body-contact zone (see Figure 11).
Pertinent to the Shroud's and our sub-sample's superficial surface discoloration, research shows that at the beginning of the crystal formation process, small crystallites rise through the bulk of the sample to the surface of the water where they are trapped by surface tension. It is speculated that the crystals may nucleate on bubbles of gas, gain buoyancy from them, and thus rise to the surface (14). Additionally, as previously described, the calcium carbonate impurities in ancient linen would have been suspended and concentrated at the cloth's surface by the surfactant property of a *Saponaria officinalis* solution and evaporation. This same scenario would apply to our modern-day, starch-coated/sized linen.
In the previously-described Nitowski study, an image was obtained in the areas of the manikin's body that retained heat the longest (chest and back). Heat would serve to more rapidly dehydrate the surface starch layer on the linen and accelerate precipitation of calcite crystals. This explains Adler's report of significantly more surface calcium in the image fibers exposed to a longer duration of heat in Nitowski's sample, as well as the previously reported x-ray data on the Shroud showing higher calcium concentrations in image versus non-image areas. Although no intentionally-directed heat source was applied to the surface of our sub-sample, the material was handled frequently by several individuals. The discolored region, which began to appear approximately one month after the experiment concluded, was identified by researchers at OSU as a "fingerprint". However, it is

unclear whether the heat and sweat from handling the sample contributed to the disproportionate discoloration. A subsequent experiment (in process) demonstrates that the addition of a mild acid (white vinegar) to the surface of linen processed via the protocol described in this paper, is capable of rendering a targeted discoloration similar to that of our sub-sample.

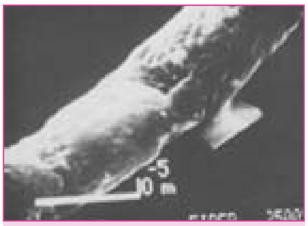
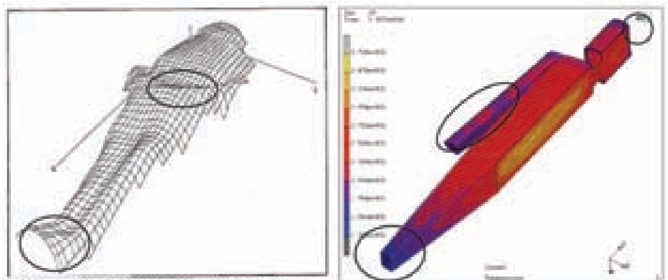


Figure 11. Microscopist Walter McCrone identified calcite on one of the Shroud fibers he examined. Note the crystal's stem-like attachment to the fiber demonstrating it is not surface debris.


Our hypothesis may also explain the Shroud image intensity as related to cloth-body distance studies performed by Jackson, Jumper and Ercoline. This group found that the VP-8 image modeled relief variations z of a human form over small scale horizontal distances (Ax,Ay = 10 cm) but "generally failed to model relationships of vertical relief between image locations separated by large scale distances" (15). The group compared distortions from an anatomically-correct human form with the VP-8 rendering of the Shroud. The derived reference surface produced a geometric representation as to how the Shroud's VP-8 image differs in relief from a plausible body shape (see Figure 12). Most notable differences were observed in the lower arm, left leg and, most of all, in the feet region.

The large-scale vertical relief discrepancies described above can be explained by post-mortem cooling patterns. A three-dimensional Finite-Element model of the human body to simulate post-mortem cooling containing different tissue compartments with different thermal tissue properties yields considerable evidence to explain the Shroud vertical relief incongruencies (see Figure 12). "The initial temperature field is modeled inhomogeneously with a gradient between body core and shell. All heat transfer mechanisms like conduction, convection and radiation are calculated according to their physical laws" (16). Comparisons with the geometric representation showing differentials in the Shroud's image compared with an actual body produce a striking correlation (Figure 12). In more rapidly cooling areas, such as the lower arms and feet, the Shroud image is faintest. Further, the model shows that the top of the head area cools rapidly. This may explain the lack of image on the Shroud cloth of the top of the head.

Jackson, Jumper and Ercoline also recognized a significant difference between the ventral and dorsal images. "Although a distance correlation for the dorsal image (or lack of it) has yet to be established, it is of interest to compare shading magnitudes to the frontal image. For the frontal image, we may consider an estimated supported weight of the Shroud, 0.39 kg, distributed over a smaller estimated contact area (nose, pectorals, hands, knees, forearms, and feet), 1100 $cm^2$ for an average pressure of 0.35 $g/cm^2$. However, the nearly 2-order of magnitude expected difference in pressure between frontal and dorsal contact regions does not appear to be reflected in the VP-8 representation of frontal and dorsal shading (either in relief amplitudes or plateau effects indicating image intensity saturation)" (17). As illustrated by Nitowski, differential cooling of the backside of the corpse would have occurred due to its placement on the cold limestone slab. This reduction in heat would have reduced calcite precipitation thus subduing discoloration on the dorsal side of the Shroud.



Geometric representation as to how the VP-8 image of the Shroud image differs in relief from a plausible body shape (Jackson, Jumper, Ercoline, 1984).

Three-dimensional Finite-Element model of the human body to simulate postmortem cooling (Mall and Eisenmenger, 2005).

Figure 12.

**CONCLUSION**

Although the results of this preliminary study, to model the principle characteristics of the discolored image fibers on the Shroud of Turin are compelling, several other experiments need to be conducted under controlled scientific conditions. This experiment and hypothesis are far from exhaustive or sufficient to answer the many questions about the Shroud image. Specifically, testing needs to be carried out using linen prepared in the same manner as ancient cloth. Most importantly, testing needs to include production of half-tone, spatially-encoded images that meet the characteristics found on the Shroud. This experiment could explain the appearance of the vertical-relief pattern observable on the Shroud. In addition, future testing needs to include the various unique parameters occurring in a Jerusalem tomb microenvironment. Additionally, work needs to be done to determine the chain reaction of events required to produce the discoloration seen in this experiment and on the Shroud.

However, given the success of this experiment, we can now amend the earlier hypothesis of Rogers and Arnoldi (2003) to incorporate a role for calcium carbonate in image formation. Along with other impurities such as iron and magnesium, which are also found in hard water, calcium carbonate would have been suspended by the surfactant property of *Saponaria officinalis* that concentrated at the cloth's surface by evaporation. The evolving precipitation/growth of calcite crystals would have been differentially induced by post-mortem cooling patterns in various regions of the body; thus, yielding the wide range of color variation found throughout the length of the cloth. These variables would have been influenced by differing properties of the individual yarns, including banding, which is clearly seen on the Shroud and is responsible for variation in color intensity differentials when compared to adjacent yarns, e.g., next to face/hair. According to the *Cambridge History of Western Textiles*, "Tapestry-woven coverlets and hangings were characterized in Hellenistic and early Roman times by 'shaded bands', which incorporated subtle colours of graded yarns. Combined later with figured designs, shaded bands had vanished by the fourth century" (18). This known time designation for the occurrence of shaded bands argues for an ancient origin of the Shroud cloth.

The appearance of deeper coloration in ventral/front regions for body parts closer to the cloth, e.g., nose, can be explained by higher surface heat reaching the cloth as compared to regions not directly in contact with the cloth. The large-scale relief discrepancy noted on the Shroud image can also be explained by post-mortem cooling patterns and positioning of the corpse in relationship to the cold limestone slab. Further, the fully established image would have appeared over the course of several weeks; thus, would not have been present immediately after death. The delayed appearance of any type of image may explain, if the Shroud does represent Jesus' burial cloth, why the image is not mentioned in the biblical accounts describing immediate post-crucifixion details. However, it should be pointed out that the success of this hypothesis does not speak to the issue of whose body was wrapped in the Shroud or the exact time period of the image-creation occurrence.

## REFERENCES AND NOTES

1. R. Rogers, *Thermochimica Acta* **425**, pp.189–194 (2005).
2. R. Roger, A. Arnoldi, The Shroud of Turin: an amino-carbonyl reaction (maillard reaction) may explain the image formation in: Melanoidins, , A. J. Ames, ed., *Office for Official Publications of the European Communities, Luxembourg* **4**, pp. 106-113 (2003).
3. J.H. Heller, A.D. Adler, *Canadian Society of Forensic Science Journal* **14**, pp. 81-103 (1981).
4. R.A. Morris, L.A. Schwalbe et al., *X-Ray Spectrometry* **9(2)**, p. 44 (1980).
5. R.A. Morris, L.A. Schwalbe et al., *X-Ray Spectrometry* **9(2)**, p.45 (1980).
6. R. Roger, A. Arnoldi The Shroud of Turin: an amino-carbonyl reaction (maillard reaction) may explain the image formation in: Melanoidins, A. J. Ames, ed., *Office for Official Publications of the European Communities, Luxembourg* **4**, p. 109 (2003).
7. J.H. Heller, A.D. Adler, *Canadian Society of Forensic Science Journal* **14**, p. 98 (1981).
8. E. Nitowski, The field and laboratory report of the environmental study of the Shroud in Jerusalem, *Carmelite Monastery*, p. 35 (1986).
9. R. Rogers, personal communication, Oct. 31, 2001.
10. S.F. Pellicori, M.S. Evans, *Archaeology*, Jan/Feb, pp. 34-43 (1981).
11. R. Rogers, *Thermochimica Acta* **425**, p. 192 (2005).
12. G. Montes-Hernandez et al., *Journal of Crystal Growth* **308**, pp. 228–236 (2007).
13. S.M. Hashmi, H.H. Wickman et al., *Physical Review E 72*, 041605 (2005).
14. S.M. Hashmi, H.H. Wickman et al., *Physical Review E 72*, 041605-2 (2005).
15. J.P. Jackson, E.J. Jumper et al., *Applied Optics* **23(14)**, p. 2248 (1984).
16. G. Mall, W. Eisenmenger, *Legal Medicine* **7**, p. 70 (2005).
17. J.P. Jackson, E.J. Jumper et al., *Applied Optics* **23(14)**, p. 2250 (1984).
18. D. Jenkins, David (ed.). *The Cambridge History of Western Textiles* Cambridge: Cambridge University Press, 1, p. 113 (2003).

**M. SUE BENFORD*, JOSEPH G. MARINO**

***Corresponding author**
**2408 Sovron Ct.**
**Dublin, OH 43016**
**USA**