PART SIX

Examination and Documentation Techniques

Digital Acquisition, Reconstruction, and Virtual Interpretation of Dunhuang Murals

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Abstract: *Acquisition of information on cultural heritage is important work. In this paper, we discuss digital acquisition equipment applicable to large-scale paintings; introduce a series of criteria for acquisition of digital images and the technology for error control of image mosaicing; and present a method for 3D modeling of color statues using a 3D scanner and describe the key technology used for texture acquisition of polychromed statues. Finally, we discuss the creation of a virtual exhibit for the Mogao Grottoes at Dunhuang.*

The cave temple mural paintings of the Mogao Grottoes at Dunhuang are famous throughout the world. Zhejiang University's Artificial Intelligence Institute is using image processing, virtual reality (VR), and artificial intelligence technologies to digitally document the murals for a virtual exhibit that will allow more people to enjoy the cave paintings.

The Dunhuang mural paintings and statues have high research and artistic value, but it is hard to acquire images digitally because the murals are very large and the shapes of the statues are complex. A research project was developed for digital acquisition of the painted caves and statues and for determining the best way to display the digital data in real time and in VR settings. The results of this work are presented in this paper.

Digital Image Acquisition of Dunhuang Wall Paintings

Digital photography of the Dunhuang wall paintings requires that data acquisition be factual and without subjective influences. That is to say, the photography is an engineering challenge, not an artistic production. Therefore, it is important to establish criteria to ensure that the process fulfills all requirements.

Photographic Platform

We designed a photographic platform system that is convenient and flexible and that can be used to obtain image data of wall paintings with high precision and low error. The camera is mounted on the platform, which includes a set of sliding rails, pulleys, a steel frame, and a pedestal. With this system, we can image three configurations of wall paintings: (1) where the area in front of the mural is wide, (2) where the area in front of the mural is narrow, and (3) where the mural is in a corner.

Photography of Paintings in Normal Configuration. Most large paintings can be digitally imaged using the photographic platform if they are flat and rectangular and the area in front of the mural is wide enough. Two main operations are performed during photography of paintings in the normal configuration: the camera platform moves in a horizontal direction and in a vertical direction. These two operations guarantee that the camera's visual angle covers the entire painting.

Photography of Paintings in Corner Configuration. For digital imaging of a mural located in a corner, the photographic platform is oriented to the corner, such as the vertical corner between two walls or the horizontal corner between wall and ceiling. The normal photography arrangement can be used to deal with a wall painting around the horizontal corners by adjusting the tilting angle of the camera platform. The corner photography arrangement can be used for wall paintings around the vertical corners by moving the camera platform along the main post vertically.

These photographic arrangements provide a customized design based on specific requirements and practical needs. Compared with traditional photographic methods, the design of the digital photography platform can be improved significantly for efficiency and accuracy. This platform system has been used at the Dunhuang Academy's Conservation Institute for the research work described here. The system is easily assembled and disassembled. With some modifications, the system can be used to photograph the large scale of cultural artifacts. For example, it was used successfully for the digital acquisition of a large Ming dynasty map, measuring 4.0 by 4.2 meters, that is part of collections stored in the Chinese History Archive Office.

Postphotography Processing: Error Control and Brightness Adjustment

After photography, individual images of the mural are "stitched" together to create a composite image of the entire wall painting. During the stitching process, loss of resolution and precision occurs. The main reason for this is not the stitching process itself but the photographic process. The camera's position, lens distortion, and the undulation of the wall's surface cause errors.

To control error, we first identify the camera's parameters. Using these parameters, we can calculate the relations between distortion and distance. We also can decide on the range that is valid in the separate pictures and control the errors according to our requirements.

If the distance between the camera and object is not the standard distance, as shown in table 1, one should select the standard distance for enough pixel resolution, which is a bit smaller than the real distance. For instance, if the real distance between camera and object is 2.3 meters, then the selected standard distance should be 2 meters. Based on the lens used, one can find the number of pixels that one edge of a selected pane contains, which is defined as $S_{len-opt}(L, Len)$. L is the selected standard distance, and Len is the lens used.

Table 1 Pixel* Chart for Selected Camera Lens and Distance from Object

Distance	1 m	2 m	3 m	5 m
Lens 1	750	1030	1310	1540
Lens 2	710	960	1200	13,809

* Pixel is defined as $\{S_{len-opt}(L, Len)\}$

The digital image's resolution, which must be decided before photography, must be high enough to guarantee research quality and visual appreciation. We know from practical experience that the digital image's precision should be at least 6.25 pixels per square millimeter. If the original mural is a fine line drawing, such as the *Thousand Hand Guanyin* in cave 3, the resolution of the digital image must achieve 9 pixels per square millimeter to fulfill the necessary requirements.

Last, the effects of surface undulations of the wall must be considered. Suppose the lean of the wall is not greater than θ and the required resolution is M pixels per square millimeter; we chose a lens (Len), the visual angle of which is φ; and the resolution of the camera lens is $W \times H$.

Then, the distance (in meters) between the camera and wall is

$$L = \frac{W \cos\theta}{2000\sqrt{M}} \cot\frac{\varphi}{2}$$

The camera platform may not move (in meters) more than

$$\frac{S_{len-opt}(L, Len) \times \cos\theta}{1000 \times \sqrt{M}}$$

every time.

Distortion always occurs during photography. There are many complex reasons for distortion, and some cannot be measured and computed accurately. We acquire camera parameters through experimentation and estimate the valid image range to reduce the effects of wall irregularities. This method can guarantee high image resolution and small error (Xu Dan, Bao Ge, and Shi Jiaoyin 2000).

Digital images often have different brightnesses, which induces a disagreeable effect in the composite image. We used a color analogy brightness method to solve this problem. First, the camera flash was used as a light source for photography and for examination of the results. Adjustments were made to even out the light distribution. Then the adjustments were adopted for the entire photographic process.

After solving the above problem, we can establish a set of criteria for the whole process. A normal digital camera and software provide high enough precision and resolution and meet the requirements for research and exhibition. Detailed criteria can be found in Shi Yihui (2002).

FIGURE 1 Reconstructed 3D wall painting with sculptural relief.

3D Digital Image Acquisition

Based on Tape Measurement. Cave dimensions are obtained by traditional tape measurement. 3D modeling software is then used to create a reconstruction of the cave.

Based on Images. There are many curved surfaces in caves apart from the polychrome statuary, such as embossments on the wall, and it is hard to acquire 3D data of these surfaces based on tape measurement. We obtained the 3D data of curved cave surfaces from images, as shown in figure 1.

To obtain 3D data of color statues, we used a 3D scanner called Fast SCAN, which is a handheld instrument that is easy to use and transport. During scanning, the 3D data can be displayed on the computer in real time and also manipulated separately. This scanner also supports output of the standard 3D file format and can handle mosaicing of several scanned surfaces. Figure 2 illustrates use of the 3D scanner.

The main disadvantages of this 3D scanner are its range limit of 1.5 meters and its inability to capture texture.

Texture Acquisition

Most 3D scanners obtain data about structure without texture, but texture is important for the imaging of statues. Photographs of statues cannot be used directly as texture. How to make use of a set of images taken from different angles to generate a statue's texture became our research problem. This process combines knowledge of computer vision and computer graphics. We designed an algorithm that can generate a texture from multiple images (Chen Ren, Lu Dongming, and Pan Yunhe 2003). Figure 3 demonstrates the process.

Virtual Model of an Outdoor Cave Scene

Our virtual model makes use of a series of photographs to reconstruct an outdoor scene at Dunhuang. This model contains one or more sequences of photographs that support virtual visiting of the site. The user can move within the scene along the predesigned path and change direction freely at some fixed points. In this way, the user has more freedom and experiences better reality than from a panorama, although the virtual model's acquisition of data sources is less strict than with a real 3D model.

Virtual Model of an Indoor Cave Scene

The virtual model of an indoor cave scene consists of two parts: the cave's structural components and paintings and

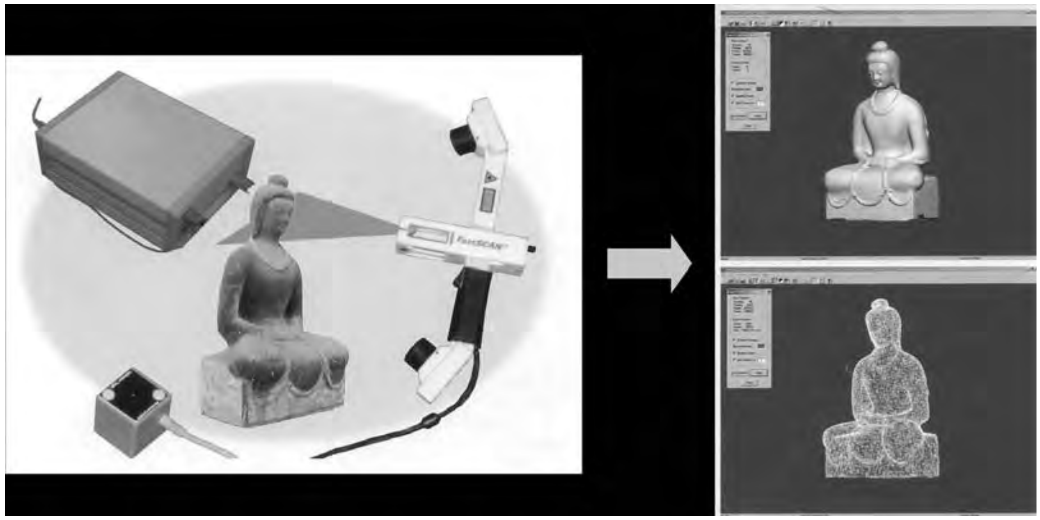

FIGURE 2 Scanner system used to obtain 3D image of statue.

FIGURE 3 Process for generating texture on a statue's image.

the cave's statues. These two models are used to express different parts of the indoor scene.

The cave structure and wall paintings model is constructed from a traditional 3D model. This model can be modified easily and rendered in real time. Special effects can be added, such as light and shadow. Obviously, this model supports full free virtual visiting. Figure 4 is an example of a modeled indoor scene.

The statue model makes use of image-based rendering (IBR) technology. Because the 3D model of a statue is complex and the amount of data is large, it is hard to render the

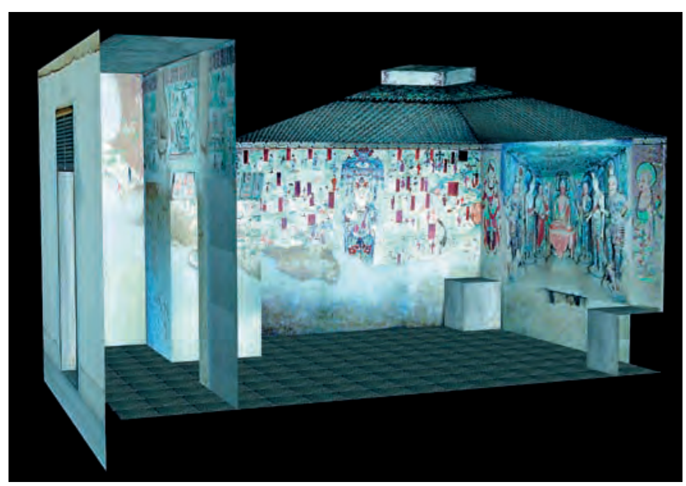

FIGURE 4 3D model of a cave interior.

3D image in real time. We make use of IBR technology and pregenerate a series of images of the statue taken from different directions. This model makes the rendering independent of the statue's complexity and depends only on the image's resolution (Zhou Tian, Lu Dongming, and Pan Yunhe 2001; Seitz and Dyer 1993–2001). Thus its requirements for computer resources are not very high, and it can run in real time on a personal computer.

The Dunhuang Caves Virtual Exhibit

Real-Time Rendering Technologies

IBR Technology. IBR technology renders a scene in real time and with high reality (Bao Hujun and Peng Qunsheng 1998). Because IBR is independent of 3D structure, the rendering time is independent of the complexity of the 3D model, but of course the 3D information of the scene is lost. IBR technology, which combines computer graphics and computer vision (Shi Jiaoying 1998), makes use of a series of images to express the 3D information of the object or scene. And during rendering, these images support the detailed information of the scene (Chen and Williams 1993). We applied IBR technology to create a panoramic image of an outdoor scene to support a virtual visit to Dunhuang, as shown in figure 5.

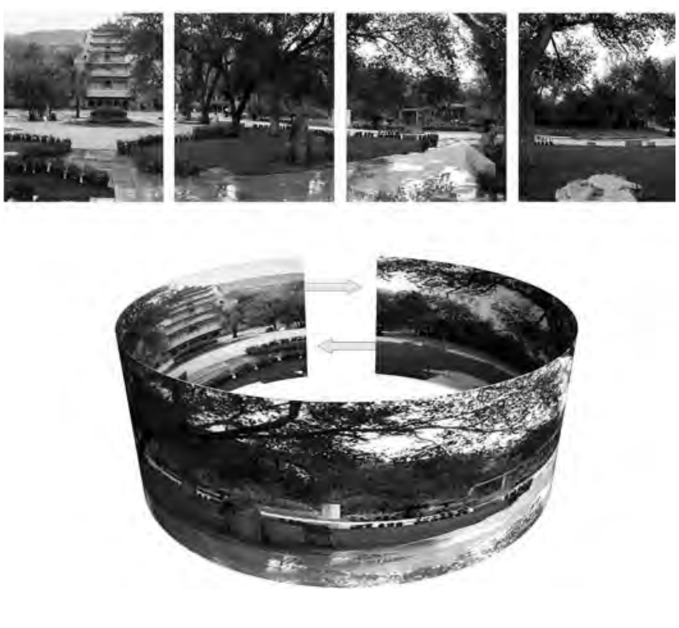

FIGURE 5 Panoramic image of an outdoor scene at Dunhuang.

Level of Detail (LOD) Technology. The advantage of the 3D model is that the 3D information is unabridged, but the triangles of the model may reach millions if the model is complex. It is a challenge to render it in real time if the model is large. Of course, we can reduce the precision of the model to reduce the rendering time to meet the requirements of real time, but this will reduce the effect. LOD technology is a good method for meeting the requirement of rendering in real time without losing the effect (Cheng Chiyi, Pan Zhigeng, and Shi Jiaoying 2001).

This method is based on a simple fact: a close object can be observed clearly, and a far object is blurry. According to this theory, we prepare a set of different precision models for one object. During rendering, the system selects the most appropriate model according to the distance between the viewer's perspective and the object.

Texture Grouping: MIP Map Technique. We also can apply the idea of LOD models to texture. Textures can be classified into several groups. During rendering, only a small number of these texture groups are close to the viewer's perspective; most groups are farther away. According to the perspective projection theory, the textures far from the viewer's perspective are scaled to very small. If every texture uses very high resolution pictures, there are two problems: this consumes a lot of computer resources and computer time; and it causes texture jitter (ragged edges) on the image.

The MIP map technology supported in Open Graphics Library (the industry standard for high-performance graphics) can solve these problems. We can define different resolutions for one texture and during rendering apply appropriate resolution texture according to the distance from the viewer's perspective. This can reduce the computing time and produce a good visual effect. This technology is very useful in our system. Because images of cave wall paintings are high resolution, using MIP map technology can reduce the rendering time significantly, without losing quality.

Reality Rendering Technology

Shadowing. A shadow expresses important relationships about an object's location and the position of the light source. Shadow is a basic element in reality graphics. Rendering reality depends mainly on perspective and shadow. So, in our system, we need shadow effects to achieve better reality.

Shadows can be computed in 3D models because they contain full 3D information. But it is difficult to compute shadow in a system using IBR because it is based on images that lack sufficient 3D information. We designed a simple model applicable to IBR to solve this problem.

According to the position of the light, we simplify the model and compute the face oriented to the light, marked as (F1, F2, . . . , Fn).

Then we compute the projection matrix for every face, Fi, marked as Ai.

$$M = \begin{pmatrix} a & b & c & d \end{pmatrix} \bullet \begin{pmatrix} x \\ y \\ z \\ q \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} \bullet \begin{pmatrix} x & y & z & q \end{pmatrix}$$

$$= \begin{pmatrix} by+cz+dq & -ay & -az & -aq \\ -bx & ax+cz+dq & -bz & -bq \\ -cx & -cy & az+by+dq & -cq \\ -dx & -dy & -dz & ax+by+cz \end{pmatrix}$$

The algorithm that computes the shadow, S, on a face is shown below.

> Starting with a face (a, b, c, d):
>
> For every light source (Li), for every position Pi (Xi, Yi, Zi), and for every face (Si), compute the projection of every vertex to the target face; the projected vertexes compose face Si' , let S' stand for the combination of all the Si':
>
> $$S' = \cup S_i'$$

Thus to obtain the shadow for light source Li: $S_{li}' = S \cap S'$.

According to the intensity of every light source, we combine projection with the scene texture and generate new texture that contains shadow. Figure 6 shows the generated shadow effects on a 3D computer image of a statue using this approach. The shadow on the statue cannot be generated by a graphics method. IBR loses a lot of information, and we propose a method based on analogy and synthesis to solve this problem.

The statues at Dunhuang are mainly Buddhas, bodhisattvas, and handmaidens. Their gestures are similar, and we can classify them into several categories. Here we describe the use of the analogy-and-synthesis method to produce shadow effects for these statues.

We obtained shadow information when the light source was placed in various positions, designated as I_{si}. Then we found the relationship between the source image, I_s, and the target image, I_d, and applied the shadow information to the target image, thus obtaining the image, I_{di}, that has the shadow effect. To achieve this result, we had to obtain information on shadows from different light positions (from I_{s1} to I_{s6}) and construct the analogy relationship between I_s and I_d. Last, we applied shadow information to I_d and acquired target images.

In the algorithm, the analogy information source is approximate to the target under different light positions. We render images from any direction and under any light source for the acquired 3D model of a statue. We then put the rendered images into the source database and thus generate a set of analogy source images, as shown in figure 7.

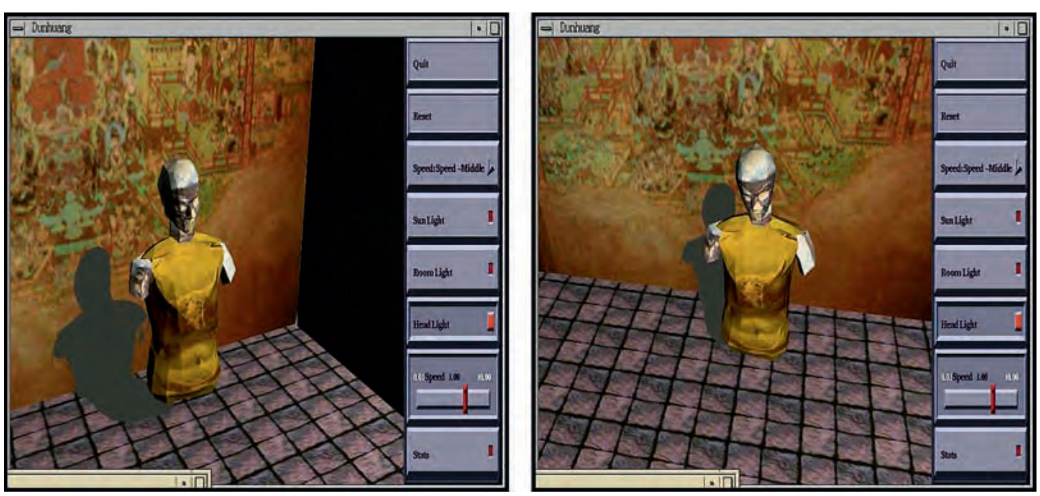

FIGURE 6 Generated shadow effects on a 3D computer image of a statue.

FIGURE 7 Analogy source images for shadowing.

Last, we acquire a color transform matrix, T_{d1}, T_{d2}, T_{d3}, . . . , T_{dn} from I_d.

Bump Mapping. Bump mapping is similar to texture mapping in that both methods make the object appear more natural. Where texture mapping expresses the object's material attributes, bump mapping expresses the lighting reality by adding surface roughness. Using bump mapping, we can achieve an effect that formerly needed a large number of triangles. Bump mapping is an extension of Phong Shading. In Phong Shading, the normal to the image is used to compute the pixel's brightness. In bump mapping, we change the angle from the normal slightly, and then the brightness of the pixel changes. Figure 8 shows a section of mural imaged, respectively, without and with bump mapping. In this example, the wall's surface roughness is generated by bump mapping, not by a large number of triangles.

Multimedia Embedded Technology

Although a virtual reality visit is impressive, making it possible to view and study every detail of a scene from different perspectives, the Dunhuang caves offer too much information to be conveyed by virtual reality alone. The cave art, which

(a) (b)

FIGURE 8 Mural section: (a) imaged without bump mapping; (b) imaged with bump mapping, showing generated surface roughness.

contains information about the ancient civilization, will be more informative to the visitor if we combine multimedia effects such as text, sound, and video with the VR scene.

To handle this additional information within the scene, we proposed a method of embedding multimedia resources in LOD models. The models of the scene consist primarily of elements such as triangles, texture, and light. When visitors walk around in the scene, some objects are expected to be selected or picked up. They could be accessed interactively during the visit if the multimedia information could somehow be linked to the objects.

After the multimedia information is linked to objects in a scene, there must be a way to display this information to the users. Typical multimedia resources include introductory text, background music, narration, video, and animation. Background music and narration can be played by a computer's sound system. However, adding introductory text, video, and animation poses challenges. We proposed two methods to solve these challenges. First, a new window other than the virtual visit window can be used for text or video output. With this method, no change in the scene is required, but the result is not impressive. A second method is to create a specific model in Open Graphics Library by altering the texture of the models. In this way, the text, video, or animation can be seamlessly embedded in the scene, but this also has disadvantages that require changing the content of the scene. Thus it is harder to implement.

Future Work

This paper outlines the technologies and methods used to develop a virtual reality exhibit for the Dunhuang murals. These technologies as applied in our system work well. Our future research will focus on how to make use of the hardware to accelerate rendering speed and enhance reality.

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High-Resolution Photography at the Dunhuang Grottoes: Northwestern University's Role in the Mellon International Dunhuang Archive

Harlan Wallach

Abstract: *From 1999 to 2003 Northwestern University, in a project funded by the Andrew W. Mellon Foundation, in cooperation with the Dunhuang Academy, photographically documented the murals on the walls of the Dunhuang grottoes: thirty-nine at Mogao and one at Yulin, 180 kilometers to the east. This effort took a two-pronged approach: coverage photography to acquire high-resolution digital images that captured the two-dimensional mural surfaces, and QuickTime Virtual Reality (QTVR) photography to record in situ the three-dimensional nature of the mural surfaces. This paper describes the evolution of the photographic techniques starting in June 1999 with cave 196 at Mogao and culminating in August 2002 with the completion of cave 25 at Yulin. It also describes our efforts in April 2003 to document murals in twenty caves with high-resolution surface and QTVR imagery and in another twenty caves with QTVR imagery alone. Our photographic techniques, in conjunction with a staff training program sponsored by the Andrew W. Mellon Foundation, have the potential to form the basis for systematic and comprehensive photographic documentation that will create a lasting archive of the Dunhuang grottoes for scholars and conservation professionals far into the future.*

In June 1999 Northwestern University, funded by the Andrew W. Mellon Foundation and in cooperation with the Dunhuang Academy, began a four-year project to photographically document the grotto murals at Dunhuang. At the end of that period, in April 2004, thirty-nine grottoes at Mogao and one grotto at Yulin had been completed. This effort was designed to produce a series of extremely high-resolution photographs and panoramic photography for inclusion in the Mellon International Dunhuang Archive component of ARTSTOR. The Dunhuang Academy's research into digital documentation at Dunhuang has been in progress since about 1993, five years before our collaborative work began on the Mellon International Dunhuang Archive.

The success of our effort required flexible thinking. The ability to address the challenges posed by the varied internal architecture of the grottoes was key to the results we achieved. In almost every situation, we were required to make adaptations to our systems and to tune our equipment and techniques to provide the highest-quality results possible.

This paper briefly describes the history of our efforts to acquire high-quality photography at Dunhuang and uses the example of cave 365 at Mogao to show in detail the techniques used and how we adapted them to a specific shooting environment.

Photographing the Dunhuang Grottoes

The project had two objectives: acquisition of high-resolution images of the two-dimensional wall painting surfaces and QuickTime Virtual Reality (QTVR) photography designed to record in situ the three-dimensional nature of the mural surfaces. QTVR is a form of panoramic photography that allows 360° imaging with panning and zoom controls. Achieving these objectives was possible because of the unique photographic and processing techniques we used. These techniques work together and inform each other. Our effort was divided into three phases, discovery, research, and production.

Discovery Phase

The June 1999 trip to China to work in cave 196 during the discovery phase was unique in several ways. To begin with, the photographic team had not previously visited the grottoes, and this trip was as much a scouting venture as an attempt to successfully capture an entire grotto. This was the only trip during which all the photography was shot on 100-speed Kodak Ektachrome film. A Nikon F5 camera was used with a variety of fixed focal length lenses. The exposed film from this discovery phase photography was carried back to the United States unprocessed. The entire cave 196 was shot without seeing a single processed image of any of the two thousand or so source images we made before leaving China. On our return to the United States, the images were processed and transferred to a Kodak PhotoCD.

The camera platform for supporting and manipulating the photographic equipment was crude. We adapted standard steel scaffolding with auto poles, iron bars, and super clamps and then mounted the entire structure on casters to facilitate moving about in the cave.

Illumination was provided by a portable battery-powered Lumedyne system. This strobe-based illumination was the only aspect of our system to remain consistent throughout the entire process. Within one year, the process would completely evolve from an analog/film-based methodology using off-the-shelf scaffolding into one based on a custom-designed and -fabricated camera platform and an image acquisition system almost entirely dependent on digital camera devices.

Research Phase

The next two trips were taken in November 1999, to photograph caves 16, 17, and 148, and in March 2000, to photograph cave 146. The approach taken during these trips was the basis for all the core innovations we would later implement in the production and completion phases. The two significant changes that occurred in our acquisition efforts took place during the November 1999 trip. These changes involved the introduction of a high-resolution digital camera, specifically the Kodak DCS 660, and high-intensity HMI lights to illuminate the entire cave at once for the QTVR photography.

The Kodak DCS 660, one of the first high-resolution digital field cameras, gave us what is now a familiar benefit of digital photography: the ability to preview the image as it is acquired. Separate images can be seen immediately and can also be "stitched" together in the cave to verify quality, exposure and focus, the geometry of image sequence, and the order and spacing, and the whole can be assembled into the final textures in the field.

Cave 148 was the first grotto in which we used high-intensity, HMI-style lighting to provide full cave illumination for the QTVR photography. QTVR photography enabled us to capture the three-dimensional nature of the grotto interior in a way that would most closely replicate what visitors would experience if they were actually standing in it. The HMI lights were pointed at reflecting "bounce" cards placed on the floor. The light bounced from these cards closely mimicked exterior daylight coming in through the entrance. This light, however, was completely controlled, and images could be acquired independently of the vagaries of actual daylight.

Caves 16 and 17 were photographed in November 1999. Due to its very small size, cave 17 (the Dunhuang Library Cave) could be shot only with a handheld camera and with a tripod. In contrast, the extremely large cave 16 required a mechanical system that would constrain and control the camera movement and allow quick adjustments. The solution was to add rollers to the camera platform so that it could be moved along a track.

This rolling scaffold system made it possible to control the camera movement as it rolled across the front of a wall mural as well as to raise the platform in controlled and measurable increments. These were the core innovations that were implemented in our photographic acquisition techniques.

Production Phase

Starting with the trip in October 2000, the process accelerated. This trip resulted in imagery from caves 249, 285, and 158, which were photographed in three weeks. With the addition of a second rolling scaffold system, two teams could work simultaneously in different caves. A third team worked in a third cave, shooting the QTVR photography. In this way, we doubled the production of the entire first year of the project. At this point manpower was a key issue, and staff from the Dunhuang Academy worked with each of our groups, thus improving the speed and efficiency of our efforts.

The participation of the academy's leadership and staff, who handled administration tasks in addition to doing the actual photography in the grottoes with us, was an integral part of our process. This collaborative approach defined the work mode for the next two years. A series of three-week, three-grotto campaigns followed: April 2001 (caves 45, 61, 254), August 2001 (caves 329, 419, 428), and October 2001 (caves 156, 322, 420).

In August 2001 we upgraded our digital equipment. This was a period of rapid technological advance during which the Kodak DCS 660 had become obsolete. Two Hasselblad ELP camera bodies with the Kodak ProBack were added to our camera equipment. This system allowed us to capture individual frames at much higher resolution, essentially three times more data, thereby decreasing the number of frames needed to cover a wall mural. It also made the postproduction assembly of images quicker.

By April 2002 we had enough equipment and trained team members to have four photography teams working simultaneously. On the final campaign, from July to August 2003, we shot two grottoes, cave 465 (at Mogao) and cave 25 at the Yulin site. The final stage of the project for QTVR photography was in April 2003, when twenty grottoes at Mogao were photographed over a two-week period. For this work, we had upgraded our digital cameras to Nikon D100 bodies mounted on Kaidan spherical QTVR shooting heads.

In general, the in-cave illumination for QTVR photography was achieved with two sources: large HMI lights to simulate daylight and the Lumedyne strobe lights to raise the level of ambient light immediately surrounding the camera. The balance of these two light sources modeled the chamber and provided even illumination for murals closest to the camera.

Staff Training

Throughout the four-year duration of the project, training of our Chinese colleagues was an important component. One training session occurred independently of each of the acquisition trips through August 2001. At the grottoes, two shooting teams worked side by side: one team was crewed by Mellon International Dunhuang Archive personnel with support from Dunhuang Academy staff, and the other consisted of only Academy staff. This made it possible to assemble a team of Chinese personnel skilled in the project's photography techniques who would later be able to use them in Dunhuang, as well as at other sites in China. The dissemination of these jointly developed photographic techniques into areas that may provide documentation and preservation of the vast cultural resources of China will, we hope, be the final legacy of this project.

Conclusion

In a follow-up to our project, the Dunhuang Academy is exploring the use of high-resolution images for the planned visitor center. Both 2D and 3D images will be used in presentations as part of an educational program. It is hoped that this extension of our work will lead to other new ways of using imagery of this resolution and quality in research and in education, as well as form the basis of new ways to explore, understand, and preserve similar sites.

Acknowledgments

This project could not have happened without the vision, support, and guidance of William G. Bowen, president of the Andrew W. Mellon Foundation; Henry Bienen, president of Northwestern University; and Dunhuang Academy director Fan Jinshi and deputy director Li Zuixiong. My two direct associates at the Dunhuang Academy, Liu Gang and Sun Hongcai, who worked with us and supported our efforts at every step, were integral to the success of this work. The attention and focus of Don Waters, our program officer at the Andrew W. Mellon Foundation, were invaluable during all aspects of this project. My two principal American collaborators on the development of the imaging techniques were James Prinz, who accompanied me on every trip, and Stefani Foster, who was one of our principal photographers and trainers. Sarah Fraser, project director, whose original research on three of the caves was the project's initial inspiration, was invaluable to the success of the project.

Dunhuang Grottoes Conservation and Computer Technologies

Pan Yunhe, Fan Jinshi, and Li Zuixiong

Abstract: *Computer technologies play an increasingly important role in conservation work. They are being implemented in a collaborative project between Zhejiang University and the Dunhuang Academy, which aims to establish a computer-assisted conservation program that entails digital documentation, virtual reconstruction and display, and simulation of pigment color change in the wall paintings of the Mogao Grottoes. In adapting these technologies, several new techniques have been developed for digital documentation and graphic processing. This paper gives an overview of these innovations.*

The Dunhuang area is home to three sites under the Dunhuang Academy's responsibility: Mogao Grottoes, Xiqianfo Grottoes, and Yulin Grottoes, comprising 552 caves with wall paintings and sculpture. This treasury of arts faces the danger of deterioration and fading and the collapse of the cave temples (Li Zuixiong and Liang Weiying 1994: preface). Conservation of this treasury is thus urgent but overwhelming in scale. Traditional conservation methods are irreversible and sometimes unpredictable in their long-term effects. For these reasons, they require a lengthy process of evaluating methods and materials, which may significantly limit their application and scope. By comparison, computer technologies have the advantages of efficiency and repeatability and are risk-free. They can effectively aid traditional conservation methods in documenting, archiving, data analysis and management, and visual replication and have great potential for conservation of the grottoes in the Dunhuang area.

Over the past decade, we have been involved in the collaborative projects Integration of Multimedia, Intelligent Graphics, and Conservation of Arts, funded by the National Natural Science Foundation of China (1998–2001), and Digital Documentation and Virtual Display of Threatened Cultural Properties, funded by the Key Technologies R&D Program (1996–99). These projects have applied computer technologies to document data, replicate wall paintings, and develop virtual displays. They have resulted in the Virtual Navigation and Wall Painting Restoration System of the Dunhuang Grottoes, which was exhibited at the World's Fair in Hanover, Germany, in June 2000, and the book *Real and Virtual Dunhuang* (Zhejiang University Press, 2003). They have also resulted in three patented designs and programs and the development of the virtual tour system of Dunhuang Mogao Grottoes, the computer-assisted replication and restoration system of the Dunhuang wall paintings, the computer-assisted protection and restoration system of grottoes, and the program to create and display the Dunhuang style designs. The results of these projects have also been presented at conferences and published in articles. This paper presents a number of major technical innovations generated by these projects.

Digital Documentation of the Dunhuang Grottoes

Digital documentation can contribute significantly to the conservation, research, and tourism development of the three sites constituting the Mogao Grottoes. The goal of this project is to build computer-based virtual models of the grottoes, thereby providing high-resolution digital data for information sharing, conservation, scholarly research, art appreciation, and development of tourism. In adapting digital technologies and computer graphics to the two major forms of art, wall paintings and painted sculptures, we have designed the two documentation programs described below.

Wall Paintings

Wall paintings at Mogao alone measure 50,000 square meters in area. Because most of the paintings are quite large, we divide a wall surface into many regions and shoot area by area so as to acquire high-resolution photographs using flash illumination, which, when patched together, produce a high-resolution image of the whole. The digital cameras are high resolution and high quality. So far several dozen grottoes have been photographed.

There has been no systematic and standardized operational procedure developed for photographing wall paintings. A traditional method is to shoot from preselected positions after mapping the target wall, which results in photographs that are difficult to piece together. To overcome this problem, new shooting platforms and a new operational procedure have been designed, both of which have been patented.

New Shooting Platforms and Procedure

There are three types of wall paintings: large and unobstructed, small or obstructed (by other objects such as altars), and corner. A shooting platform has been designed for each type. The platform for the first type consists of a sliding board on two rails, two side frames that are affixed to the sliding board, and a frontal frame that is attached to the two side frames. The frontal frame is an independent unit holding a camera and a flashlight and can be used on the second and third types of platforms. The rails are laid parallel to the wall, and the camera and flashlight can move horizontally by sliding the board. The frontal frame can slide on the side frames vertically. The camera and flashlight can move synchronically both horizontally and vertically while maintaining the same distance to the target wall. For the second type, the frontal frame is attached to two horizontal beams but can slide horizontally on them. The two horizontal beams are attached to two standing and fixed poles and can slide vertically. So eventually the camera and flashlight can move both horizontally and vertically (fig. 1). For the third type of fresco, the frontal frame is attached to one standing and fixed pole and can slide vertically on it.

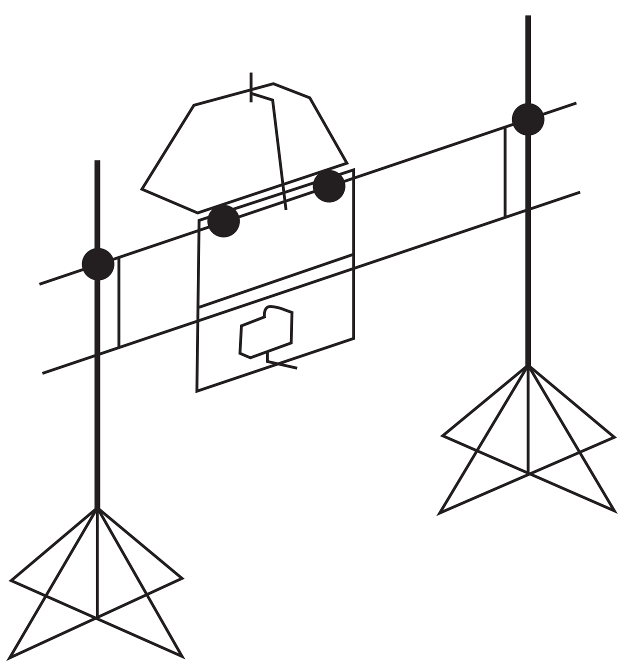

FIGURE 1 Shooting platform, designed by Zhejiang University, 2001, Patent no. CN 01209426.9.

The working procedure consists of the following steps:

1. Measure the wall and divide it into regions, the sizes of which can be calculated based on the desired resolution.
2. Install flashlight and camera on the shooting platform.
3. Adjust camera and flashlight.
4. Test shooting.
5. Begin shooting and record shooting settings, such as position, serial number, resolution, and light.
6. Store photographs on the computer.
7. Patch and edit photographs.

Resolution loss is expected during digital documentation. The loss can be caused by uneven walls, projection distortion, and change of shooting position. It can also result from the fact that resolutions of individual photos vary, and the resolution of the patched photograph is identical to the lowest one. To minimize this loss, each cause is examined, and a course of action to minimize its effect is determined, as follows:

1. We determine the distortion of a lens by testing it. With this we can correct the distortion of each photograph.
2. We select the most cost-effective resolution for the project. Digital documentation demands high

resolution, which not only increases the workload but also consumes computer memory resources. Based on our experience, a resolution of 6.25 pixels per square millimeter is sufficient for documenting most wall paintings, but for those that were painted with fine lines, such as the thousand-arm Avalokitesvara in cave 3 at Mogao, the resolution must be raised to 9 pixels per square millimeter to achieve adequate photographic quality.

3. Finally, we consider the inclination of a wall. In this case it is necessary to determine the angle of deviation from the vertical, and knowing the camera and lens specifications, we are able to develop a complete algorithm for calculating the compensation required.

Painted Sculptures

For 3D objects such as painted sculptures, we use a 3D scanner to acquire their geometric models with millimeter accuracy. Operational procedures have also been designed for painted sculptures of various sizes and various positions. The currently available scanner, however, cannot record the rich color information of painted sculptures. To overcome this defect, we take digital photographs around painted sculptures and put them on the scanned monochrome models using a method previously developed that employs three types of algorithms: projection transformation, triangle morphing, and mosaicing (Chen Ren, Lu Dongming, and Pan Yunhe 2003: 902). The patched photograph is usually not seamless because it is difficult to maintain the exactly identical positions and lights and shades. So we use patching and blending, the Szeliski program in particular, to harmonize them.

This method takes into consideration the shooting conditions during the mosaicing and blending processes and has advantages, we believe, over the texturing method advanced by the Italian National Research Council in that it produces a complete surface of the object that is visual and unambiguous. We can revise texture and edit the image directly, which is useful for virtual restoration of objects and the construction of a multimedia database.

Virtual Display

An Integrated Model

The Virtual Navigation System of the Dunhuang Grottoes is intended to include a broad spectrum of information, including external environments, architectural structures, wall paintings, painted sculptures, and an audio information system. We have proposed a metamodel to integrate the models designed for the above-mentioned tasks. The framework of the metamodel is shown in figure 2.

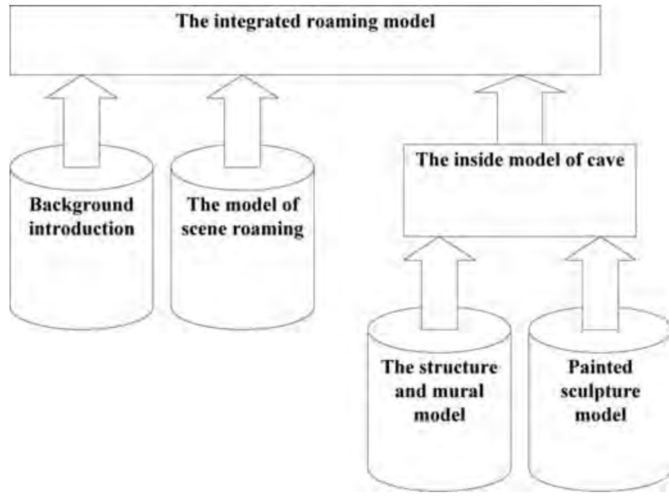

FIGURE 2 Integrated model of the Virtual Navigation System of Dunhuang Grottoes, created by Zhou Tian, 2002.

Rendering Based on the LOD Group Model

Rendering is a process of transforming still photographs into motion video, and for this purpose we use the LOD (level of detail) group model. This modeling program first divides the triangles in a 3D model into several groups, which are linked with each other (Diao Changyu 2003: 22). The division of LOD groups is shown schematically in figure 3.

During the rendering process, each group of triangles is textured with one level of detail. The LOD of each group is determined by the distance between the group and the viewpoint. The group nearer to the viewpoint is given the higher complexity and resolution; the one farther from the viewpoint is given the lower complexity and resolution. The working process of the grouping LOD model is shown in figure 4.

Computer-Assisted Wall Painting Replication

Conventional Method

The conventional working procedure for documenting the condition and copying the wall painting consists of five steps: (1) shooting positive photographs of the painting; (2) magni-

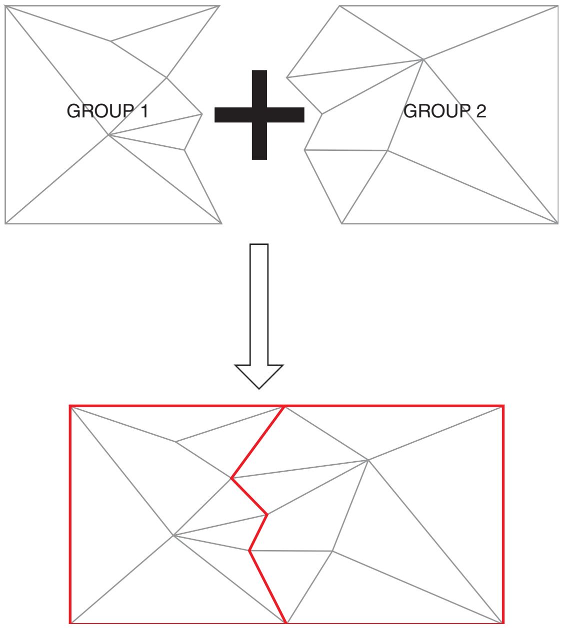

FIGURE 3 Grouping LOD model, created by Diao Changyu, 2003 (top: seen up close; bottom: seen at a distance).

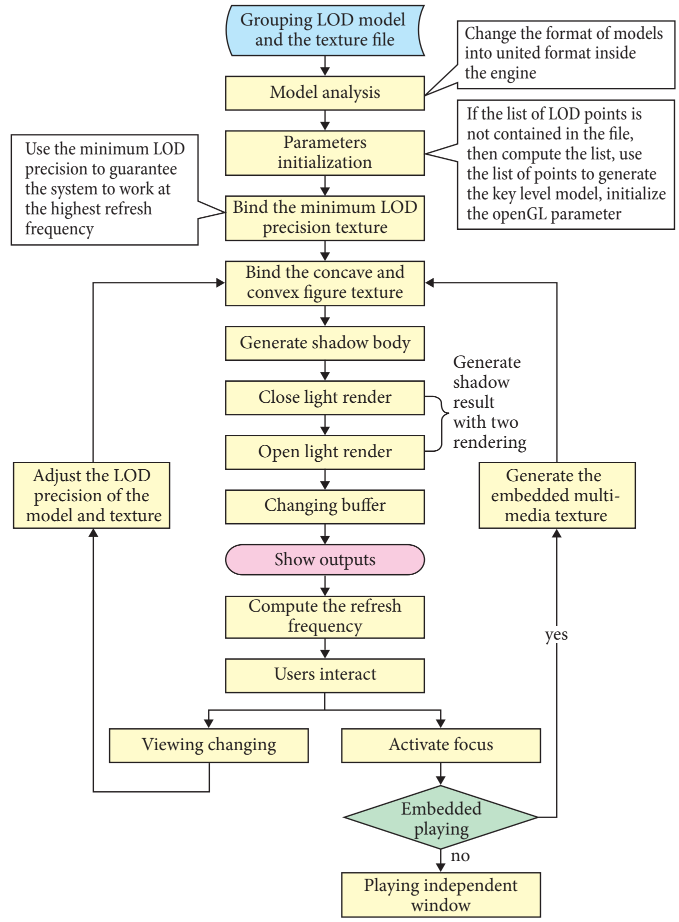

FIGURE 4 Rendering of engine process of the grouping LOD model.

fying the positive film to the original size; (3) editing the film based on the original; (4) copying a line drawing onto a piece of paper; and (5) coloring the drawing based on the original. The production of the copy is extremely time-consuming and labor-intensive. An area of a few square meters may take a year to complete. Coloring also requires knowledge in the fields of chemistry, physics, and art history and is an equally sophisticated process; a casual mistake would cause a great loss of time and labor.

Key Techniques of Computer-Assisted Replication

Intelligent computer techniques enable us to overcome the limitations of the conventional method in both line drawing and coloring as described below.

Computer-Assisted Drawing. Conventional algorithms of partitioning images and acquiring line boundaries cannot satisfy artists' demand for detail. The computer may enable us to acquire more realistic replications of images. To explore this potential of the computer, we have conducted a number of technical studies. First, we used accurate boundary acquiring techniques. The commonly used techniques for partitioning images are threshold, edge detection, region growing, and recursive algorithm. These methods can produce good pictorial effects when used to segment gray images, but when they are used to segment color images, the effect is not satisfactory. In most cases, we cannot obtain the ideal effect by using one method. We were able, however, to improve the effect by applying variously combined segmentation methods to different target regions (Li Xiangyang et al. 1998: 637), thereby effectively determining edge detection on the wall paintings (Wei Baogang et al. 2001: 60).

Next, damaged or lost areas are "replaced" with pictorial models (Wei Baogang and Pan Yunhe 1998: 260). We have built up a database of vector graphics of line drawings and colors produced by contemporary Dunhuang Academy artists who use traditional copying methods. From this database, the best selection is made for replacing or mending the damaged areas. Last, the lines are refined by alternately using the well-developed vectorizing technique and interpolation algorithm to simulate line drawings of various styles.

Computer-Assisted Coloring. To color the computer-generated line drawings, pattern recognition, computer graphics, and nonrealistic drawing techniques are used. First, the target areas are determined. Then the required pictorial elements and specific target regions for coloring are identified. Next, the correct colors are selected from the database using intelligent search. Based on the distinctive coloring technique and brushstrokes of Chinese paintings, we have developed models that imitate conventional brushstrokes. With these models, the spirit of the brushwork of the paintings is re-created to the extent possible.

Conclusion

It appears that the application of digital technologies and computer graphics is beneficial to the conservation of Dunhuang art. In addition, adaptation of computer technologies to the wall paintings inspires the development of new graphic techniques. In the meantime, computer technologies greatly assist conservation methods and can be used extensively in the interpretation of the sites and their art to visitors.

Acknowledgments

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Multispectral Imaging for Easel and Wall Paintings

Haida Liang, David Saunders, John Cupitt, and Christian Lahanier

Abstract: *As part of the European Union–funded CRISATEL project, a new high-resolution multispectral imaging system has been developed for the efficient, direct imaging of paintings. The CRISATEL camera, fitted with thirteen band-pass interference filters covering a wide spectral range, from ultraviolet to near-infrared (400–1,000 nm), is capable of capturing an image of 12,000 by 20,000 pixels. The camera was tested with a new pigment chart developed as a potential museum standard as it has a wider color gamut and is more representative of the pigments found in easel and wall paintings than the Macbeth ColorChecker chart used in the past. The major improvements over the VASARI multispectral system, developed previously at the National Gallery, is the potential portability of the new camera and the possibility of reconstructing the spectral reflectance per pixel of a painting rather than calculating simple colorimetric data under a given illuminant.*

In this paper, we concentrate on a laboratory version of the CRISATEL camera to assess its application to the imaging of a wall painting fragment. The multispectral data for this wall painting have been used to reconstruct color images of the painting as it would appear under different illuminants, daylight and candlelight in this instance. The spectra for each pixel have been reconstructed, and comparison with measurements made by conventional spectrophotometric means indicates good accuracy. The technique thus has potential for increasing the accuracy of long-term color monitoring over the entire surface of a painting using a noncontact technique. A series of pigment standards have also been imaged using the system, and their spectral reflectances have been reconstructed. These provide the basis of a library of spectra that could be used in pigment identification; the technique was applied successfully to four areas of the wall painting fragment studied.

Since the late 1980s, the National Gallery in London has been engaged in the development of multispectral imaging systems. The initial aim of this research was to monitor long-term color changes in paintings, but the scope of the research has since expanded to encompass accurate color imaging for conservation documentation and, most recently, to investigate the potential of multispectral imaging as an additional method to assist in pigment identification. Although much of this research has centered on easel paintings, the techniques apply equally to wall paintings. We have recently begun to explore the challenges of applying the technology to the examination of paintings on walls.

These imaging systems have been developed through a series of pan-European research initiatives, beginning with the VASARI project,[1] which produced the first multispectral imaging system to examine paintings, based on a monochrome digital camera and a filter system that provided seven bands across the visible range from 400 nanometers (nm) (blue) to 700 nm (red) (Burmester et al. 1992: 201–14; Saunders and Cupitt 1993). The VASARI system made efficient colorimetric measurements on the surface of the painting using a series of targets to calibrate the seven-band data. The color information was stored as standard CIE Lab color coordinates (CIE 1978), and although the seven-band data were also archived, no attempt was made to reconstruct the spectra. The color accuracy was determined by comparing the color data obtained from imaging the twenty-four colors of the Macbeth ColorChecker chart with color data for the same patches measured spectrophotometrically. Over the course of ten years, the calibration process was refined to reduce the color error to the point where it was close to a just-visible difference (Martinez et al. 2002). The main drawbacks of VASARI systems are that they are more or less immovable once installed, they can measure only smaller paintings, and they were mainly used for producing accurate color images rather than for deriving convincing reconstructions of the reflectance spectra on a per-pixel basis.

The European Union–funded CRISATEL project developed a new high-resolution multispectral imaging system to image paintings and other 2D objects (Lahanier et al. 2002).[2] The CRISATEL JumboScan camera, fitted with thirteen band-pass interference filters, covering a wide spectral range from visible to near infrared (400–1,000 nm), is capable of capturing an image of 12,000 by 20,000 pixels. The scanner was tested with a new pigment chart developed as a potential museum standard. The new chart covers a wide color gamut and is more representative of the pigments found in modern and old master paintings than the Macbeth ColorChecker chart used previously. The major improvement of CRISATEL systems over the existing VASARI multispectral system developed previously at the National Gallery is the potential for reconstruction of the spectral reflectance per pixel of a painting rather than simple colorimetric data under a given illuminant.

The results presented in this paper were obtained using a laboratory version of the CRISATEL system constructed at the National Gallery (referred to here as the NG CRISATEL system) during the development of the large CRISATEL JumboScan camera in Paris (Ribes et al. 2003). The NG CRISATEL system is based on the same set of thirteen filters used with the full CRISATEL system and a simple commercially available camera (Haida Liang, Saunders, and Cupitt 2005).

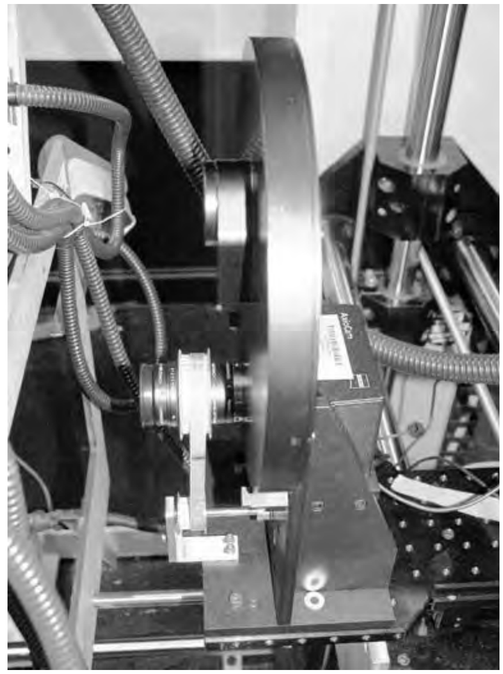

FIGURE 1 NG CRISATEL multispectral imaging system in use at the National Gallery, London.

The NG CRISATEL Multispectral Imaging System

The laboratory version of the CRISATEL multispectral imaging system in use at the National Gallery is based on a monochrome digital camera, Zeiss AxioCam, with a cooled CCD sensor and fourteen-bit electronics fitted with a filter wheel holding the same thirteen interference filters used in the JumboScan. The CCD detector in the camera is a Sony 1,300 by 1,030 pixel sensor with pixel size of 6.7 micrometers, capable of sampling at 3,900 by 3,090 pixels in microscanning mode (fig. 1). The lighting system consists of two identical 82-volt, 410-watt tungsten lamps connected through optical fibers to six outlets that are evenly placed around the optical axis, illuminating the target at roughly 45°. The filter wheel is placed between the detector and the Schneider Componon-S lens (80 mm focal length). The camera needs to be refocused with each change of filter because of the variation in filter thickness. This is achieved by adjusting the lens focus automatically. The closest object distance gives a resolution of 20 pixels per millimeter on the painting. An f-number of 5.6 was chosen to give the highest efficiency without vignetting and distortion. For use in the laboratory, both the camera and the lights are mounted on an X-Y scanning stage such that the illumination and viewing geometry are fixed over the entire scan.

The response of the CCD was found to be linear over almost the entire dynamic range, and the mean dark current, which corresponds to the thermal noise of the device, was found to be constant with exposure time. Each series of twelve dark frames was taken at the same exposure as for the target frame, to produce master dark frames to be subtracted from target frames. Exposure times per filter were adjusted such that the frames were not saturated and the total counts accumulated were the same for each filter when a perfect white target (i.e., 100% spectral reflectance across the channels) was imaged.

A white Teflon (PTFE) board was used for flatfielding, that is, correcting the inhomogeneity of the illumination and the variation in pixel-to-pixel response of the detector for each filter. A Spectralon white from LabSphere was used as a white spectral target to correct for the spectral response of the system. The central area of the dark-subtracted and flatfielded image of the spectral white target was then used to spectrally calibrate the target frames.

Assessing Quality of Spectra and Color

To check the accuracy of the spectra measured with the NG CRISATEL system, two kinds of pigment-based color charts were imaged: (1) the Macbeth ColorChecker DC chart with 240 color and gray scale patches and (2) a chart, developed for the CRISATEL project by the French pigment manufacturer Pébéo,[3] with 117 color and gray patches duplicated in both varnished (glossy) and unvarnished versions (the Pébéo chart is more representative of artists' pigments and is a potential museum standard). A Macbeth ColorChecker chart with only twenty-four color and gray patches was also used as a routine test chart for each painting scanned. While the commercially available Macbeth charts are pigment based and have a wide color gamut, they were thought to be unrepresentative of the spectral reflectance of pigments found in old master paintings.

For camera systems designed to reproduce accurate color images of the original, there is a standard colorimetric measure of the quality of the system that gives a clear indication of the significance of a color difference to a human observer, namely, a mean ΔE for a color chart (a ΔE ~ 1 usually means a just-discernible color difference for a human observer). In the case of a multispectral system designed to reproduce not only accurate color but also accurate spectra, an assessment of a combination of a mean ΔE and a mean rms (root mean square) spectral difference between the measured or reconstructed spectra and the "standard" spectra of a color chart measured with a spectrophotometer is needed. These two parameters are used here to judge the quality of our system. In particular, color difference will be expressed in terms of ΔE_{00} under D65 illumination and viewed by a 1931 2° CIE standard observer (Luo, Cui, and Rigg 2001), and rms spectral differences will be calculated between 400 and 700 nm at 10 nm intervals unless otherwise specified.

A simple cubic spline was found to be sufficient to recover the spectral reflectance from multispectral images (fig. 2). Table 1 summarizes the differences in terms of rms spectral differences and ΔE_{00} between the spectral reflectance obtained from the NG CRISATEL multispectral system and those from the Minolta spectrophotometer for the various test charts. The color difference was found to be 1.2 and 1.9 ΔE_{00} units for the various test charts. In this case, the Minolta measurements were made by collecting reflected light from a circular area of 3 mm in diameter, and the multispectral measurements were averaged over an area of 3.5 by 3.5 mm². The differences listed in table 1 include both intrinsic differences between the multispectral system and the Minolta spectrophotometer and random measurement errors and interpolation errors. Some of the intrinsic differences between the systems reflect a limitation in the multispectral system; for example, unlike a spectrophotometer, the multispectral system is an open system in which each measurement area is affected by scattered light from its surroundings. On the other hand, the spectral and color differences that resulted from the difference in illumination and viewing geometry between the systems are not a limitation of the multispectral system. In other words, if we can find a spectrophotometer with the same illumination and viewing geometry as the multispectral system, then the spectral and color differences will be less than those listed in table 1.

Table 1 Spectral and Color Differences, CRISATEL System vs. Minolta cm2600d Spectrophotometer [a]

Color Chart	Spectral rms Difference	ΔE_{00}
Macbeth	0.014	1.2
Macbeth DC	0.017	1.6
Pébéo unvarnished	0.016	1.9
Pébéo varnished	0.017	1.8

[a] Mean differences between the CRISATEL system interpolated spectra and those measured with the Minolta cm2600d spectrophotometer.

Assessing Instrument Stability

The stability of the instrument is important for the purpose of spectral/color monitoring. The stability of the NG CRISATEL system was checked over a period of six months in three independent experiments using a small Macbeth ColorChecker chart of twenty-four color and gray patches. The relative spectral/color differences between the experiments were 0.95 ΔE_{00} unit and a mean rms spectral error of 1.3. The color differences are visually insignificant to a human observer; that is, the CRISATEL multispectral system is sufficiently accurate for the purpose of monitoring color or spectral changes.

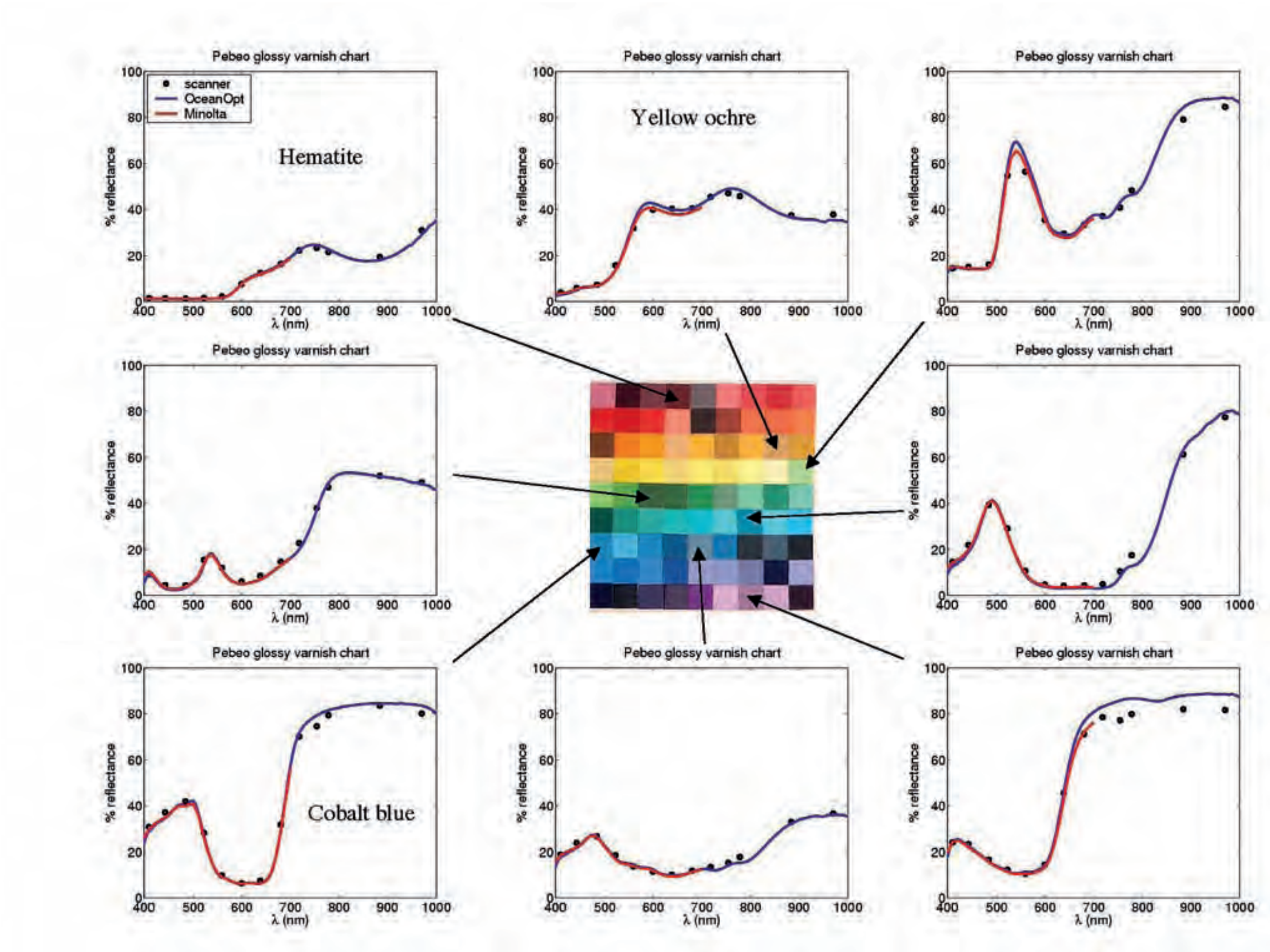

FIGURE 2 Spectra for eight patches from the Pébéo glossy color chart measured with the Minolta cm2600d and Ocean Optics spectrophotometers and compared with data from the NG CRISATEL multispectral scanner.

Imaging Wall Paintings with the NG CRISATEL System

Although the CRISATEL multispectral systems were developed for use with European easel paintings, we have also used the NG CRISATEL system to image a detached wall painting fragment to demonstrate its applicability to such painted surfaces.

The multispectral system was used to image a fragment of a fifteenth-century Tuscan detached fresco painting (*Heads of Angels,* National Gallery, London, No. 1842). In this trial a very high resolution was used; the small fragment, measuring 29 by 41 square millimeters, was scanned in twenty individual images per filter, each 1,300 by 1,030 pixels in size, with an overlap between successive images of 100 pixels. At this imaging distance, the change in image scale between filters was less than 1 pixel, and it was not, therefore, necessary to resample the images onto the same scale. The corresponding images through different filters were aligned automatically using a cross-correlation routine in VIPS, an imaging software developed at the National Gallery (Cupitt and Martinez 1996). The twenty images for one reference channel were assembled into a mosaic automatically, and images for the other channels were then assembled using the same parameters. An enlarged detail from the bottom right of the final image (rendered to show the appearance of the fragment as if illuminated by day-

FIGURE 3 Detail from *Heads of Angels* (National Gallery, London, No. 1842) imaged with the NG CRISATEL system, showing the absence of color fringes at the edges of cracks.

(a)

(b)

FIGURE 4 Color images of *Heads of Angels* rendered under (a) daylight and (b) candlelight.

light) is shown in figure 3. This demonstrates the accuracy of interchannel image registration, as no color fringes are seen at the edges of the cracks (a common problem with multiband images).

For each pixel in the final assembled image, the spectral reflectance was obtained through a cubic spline interpolation between the thirteen data points from 400 to 1,000 nm. This per-pixel spectral information allows the color of a painting to be simulated as it would appear under different illuminants. For the wall painting fragment examined here, the appearance was simulated under two widely different illuminants: daylight and candlelight. This was achieved by multiplying the spectrum of each pixel by the spectral power distribution of the chosen illuminant, with the results rendered using the 1931 2° CIE standard observer weighting functions (ASTM E 308) to give a color image of the painting under that particular illuminant (figs. 4a, b).

Pigment Identification

Visible spectrometry is not generally an efficient method of pigment identification. The surface color of an area often gives as much information as the spectra themselves, and simple visual inspection under high magnification can reveal particle size and shape—two characteristics that greatly assist pigment recognition. However, the addition of the three infrared channels to the new CRISATEL system may aid the identification of pigments by spectral reflectance, as the behavior of pigments in the near-infrared region is not necessarily evident in their color. For example, it is difficult to distinguish between indigo and Prussian blue using conventional microscopy (Berrie 1997; Schweppe 1997), but it is relatively easy to distinguish between the two from their near-infrared reflectance spectra. Comparing the NG CRISATEL system's reconstructed spectra for the Pébéo chart mentioned earlier with those measured with either of the two spectrophotometers (see fig. 2) shows that the new multispectral system is on the whole comparable to a spectrophotometer.

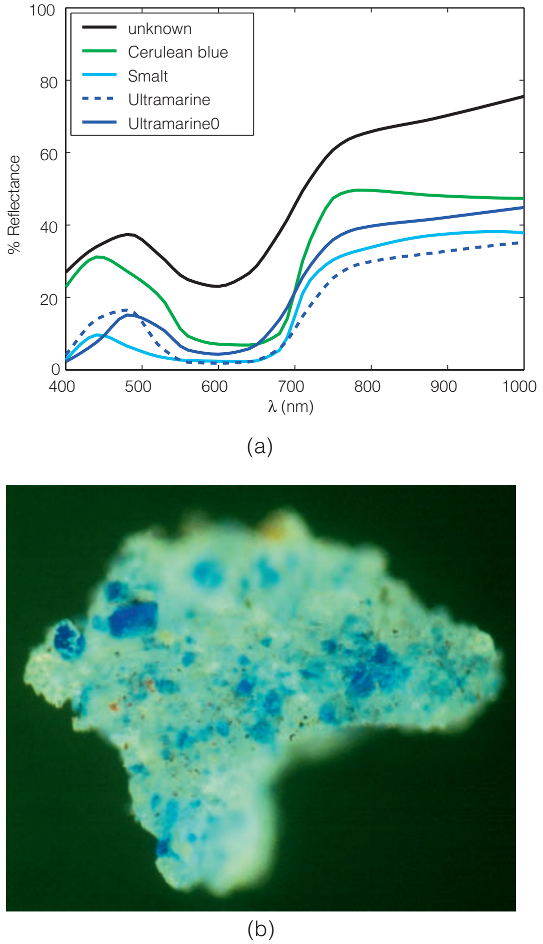

FIGURE 5 Identification of unknown blue pigment from *Heads of Angels:* (a) reflectance spectra of blue region compared with library spectra for ultramarine in linseed oil, ultramarine in egg tempera, smalt, and cerulean blue, showing the ultramarine samples to be the best matches; (b) photomicrograph under polarized visible light of blue pigment sampled from the same area of the wall painting.

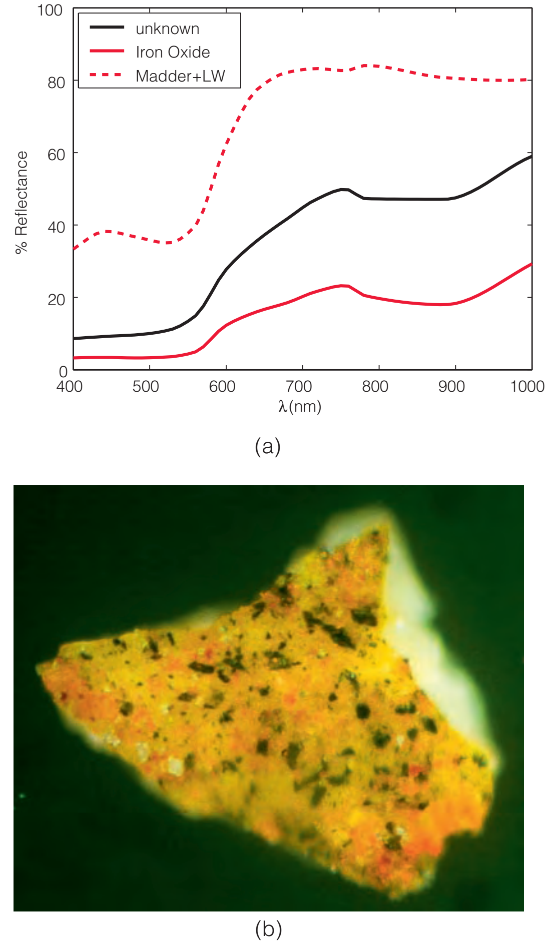

FIGURE 6 Identification of unknown red pigment from *Heads of Angels:* (a) reflectance spectra of red region compared with library spectra for iron oxide and madder lake (mixed with lead white), showing iron oxide to be the best match; (b) photomicrograph under polarized visible light of red pigment sampled from same area of the wall painting.

The ability of the multispectral system to produce tentative pigment identifications was assessed on four regions of the *Heads of Angels* wall painting fragment. These regions were the blue robe of the angel on the left in figure 4, the red fabric of the robe of the angel in the middle, the purple robe of angel on the right, and the black background on the left. For each color, the final averaged spectra were obtained from two separate regions, each comprising around 5,000 pixels (3.5 by 3.5 mm^2). These spectra were then compared with a spectral library of sixty-three historic artists' pigments to find the best match.

The NG CRISATEL spectrum for the blue pigment gave reasonable matches with spectra from two samples of ultramarine (one in linseed oil and the other in egg tempera), smalt, and cerulean blue, but the best matches are with the reflectance curves for ultramarine (fig. 5a). A small sample taken from this region and examined under the microscope (fig. 5b) shows the characteristic angular particles of natural ultramarine. From the spectra in figure 5a, it can be seen that the three infrared channels of the CRISATEL system are particularly useful in differentiating between cerulean blue and the other pigments.

The NG CRISATEL spectrum for the red pigment gives an extremely close match with a standard spectrum of an iron oxide earth pigment but a poor match with the spectrum of a red lake pigment (madder lake mixed with lead white) added for comparison (fig. 6a). A small sample taken from this region and examined under the microscope (fig. 6b) shows the characteristic particles of iron oxide.

The NG CRISATEL spectrum for the purple pigment was matched with the spectrum of iron oxide, but under the microscope it was clear that there is a red lake layer above the iron oxide layer. The spectral features of the iron oxide dominate, and the red lake is not identified using this method, demonstrating the current limitations of the technique.

It was not possible to identify the black pigment either spectrally or with optical microscopy. It was later identified as degraded tin using energy-dispersive XRF analysis.

Future Developments

We have shown that it is possible to produce high-resolution images with high color and spectral accuracy using the NG CRISATEL system with a simple off-the-shelf camera fitted with a set of interference filters. However, so far the system can be used only in a studio environment for imaging small easel paintings. While the large-format CRISATEL JumboScan is more portable than the NG CRISATEL system, it is still not suitable for high-resolution in situ imaging of wall paintings (e.g., ceilings). Currently, imaging such paintings at high resolution requires either scaffolding or a heavy and cumbersome mechanical structure to lift the camera to the upper parts of a wall or ceiling.

A portable multispectral system for remote imaging of wall paintings is currently under development. The prototype remote imaging system consists of a camera and filters similar to those used for the CRISATEL systems but mounted on a small telescope. For quick color images, a simple RGB camera can be substituted. The use of a telescope eliminates the need for scaffolding or a lifting mechanism.

The prototype is designed to have a resolution of 5 pixels per millimeter when imaging a painting at a distance of 30 meters. The pointing direction of the telescope and the focus position of the camera are computer controlled and accurately recorded as the images are taken. This will make it possible to render the wall paintings in 3D. The camera system will be automatically controlled to scan, mosaic, and render the images in 3D by a small portable computer. Both the camera system and the computer stay at ground level during operation. The system weighs approximately 20 kilograms and can be fitted into a suitcase. The portability of the system means that it can be taken to remote sites to image large paintings in situ from ground level. Details of the prototype portable remote multispectral imaging system and results from the first field tests have been reported (Haida Liang, Keita, and Vajzovic 2007).

Acknowledgments

We would like to thank Marika Spring for sampling the *Heads of Angels* wall painting fragment and providing photomicrographs.

Notes

1 VASARI stands for Visual Arts System for Archival and Retrieval of Images.

2 The term CRISATEL is derived from the full name of the project, Conservation Restoration Innovation Systems for Image Capture and Digital Archiving to Enhance Training Education and Lifelong Learning.

3 See www.pebeo.com.

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Scientific Examination of the Traditional Materials and Techniques Used in Yuan Dynasty Wall Paintings

Rocco Mazzeo, Edith Joseph, Silvia Prati, Ma Tao, Gwénaelle Gautier, and Lucien M. van Valen

Abstract: *Few publications are available on the materials and techniques used by ancient Chinese artists to create Yuan dynasty wall paintings. Most of the information that is available appears in Chinese and is not well known by the international conservation community. This lack of knowledge may affect the interpretation and reliability of scientific examinations of Chinese heritage materials. This paper presents the initial findings from a study to compare the results of a literature survey on Yuan dynasty wall painting materials and techniques with the results of scientific examinations of samples collected from murals in a Yuan dynasty Daoist temple at Yao Wang Shan in Shaanxi province, China.*

The analytical techniques used to characterize the renders, preparation layer, and paint layers of the murals are optical microscopy, polarized light microscopy, scanning electron microscopy coupled with electron probe microanalysis, X-ray diffraction, Fourier transform infrared spectroscopy, Fourier transform infrared microscopy coupled with attenuated total reflectance spectroscopy, pyrolysis–gas chromatography–mass spectrometry, gas chromatography–mass spectrometry, differential thermal analysis, Raman microspectroscopy, and ion chromatography. The results obtained from the different analytical techniques used to characterize the Yao Wang Shan mural paintings are compiled in the Diagnostic Data Archiving System (DIDARS) database.

Few publications are available on the materials and techniques used by ancient Chinese artists to create Yuan dynasty (1271–1368) wall paintings. Most of the information that is available appears in Chinese and is not well known by the international conservation community. This lack of knowledge may affect the interpretation and reliability of scientific examinations of Chinese heritage materials.

This paper presents the initial findings of a study to compare the results of a literature survey on Yuan dynasty wall painting materials and techniques with the results of scientific examinations of samples collected from murals in a Yuan dynasty Daoist temple at Yao Wang Shan (Medicine King Mountain)[1] in Shaanxi province, China.

Yuan Dynasty Murals in the Temple at Yao Wang Shan

The temple at Yao Wang Shan, built in 1272 C.E., during the reign of Zhi Yuan, contains one of the three or four remaining examples of a specific image of a Daoist painting from the Yuan dynasty. This image is called *chaoyuantu*, which can be translated as “Chart for Facing the Origin” or “Worshiping the Origin.”

Our research study was facilitated by the facts that the murals at Yao Wang Shan, unlike others with similar imagery,[2] are in their original locations and that apparently no restoration interventions had been carried out on them, except for an acrylic resin applied by one of the authors to preconsolidate some detached parts of the paint surface. This allowed scientific examinations to identify the original traditional materials and technique used.

Two murals, covering a total area of about 96 square meters, depicting the tour of the emperor and that of the queen are painted, respectively, on the east and west walls of Hanyuan Hall in the temple (fig. 1). The murals contain twelve groups of figures totaling eighty persons (emperor,

FIGURE 1 Tour of the Emperor mural on east wall of Hanyuan Hall in the Yao Wang Shan temple.

queen, high-ranking officials, concubines, and maid of honor). During the Cultural Revolution, the temple was used as a classroom, and windows were opened to let in sunlight, which destroyed part of the murals. Further damage was caused by small holes left in the walls by nails used to hang the children's school bags.

Literature Survey

Only four publications were found in our literature survey of the materials and techniques used by ancient Chinese artists to create Yuan dynasty wall paintings (Lu Hongnian 1956; Yu Feian, Silbergeld, and McNair 1988; Malenka and Price 1997; Chu Qi'en 2000).

The article by Lu Hongnian (1956) is one of the earliest publications on mural painting technique. He mentions that "in Yuan dynasty a new wet-wall painting technique was introduced using sand and clay mixed with glue for the wall, which was smoothed when still wet and painted before it was dry so that the pigments could seep into the material and become fairly safe from decomposition as long as the moisture level of the wall was under control."

Malenka and Price (1997) studied the materials and technique used to paint Yuan dynasty wall paintings that had been removed from a partially destroyed temple near Xinxiang (Henan province) and purchased in 1924 by the Philadelphia Museum of Art. Their research identified the use of clay, quartz, calcite, and fibers for the coarse render and a mixture of clay and quartz for the preparation layer. They report that proteinaceous materials were detected in each of the layers, as well as traces of conifer resin in the fine white preparation layer.

Chu (2000), in his study of the murals in Yongle Palace (Shanxi province), refers to the use of sand, loess,[3] hemp, sinew, and dried wheat straw for the coarse render and sieved loess and white paper pulp for the fine render. The prepared wall surface was then brushed with two layers of a mixture of bone glue and kaolin clay and allowed to dry before being painted.

Chu makes reference to Lu Di, one of the first generation of researchers in Dunhuang to study wall paintings, who writes that in the ancient wall paintings of the later period great attention was already paid to guard the surface against the alkalinization phenomenon that led to the production of a basic environment responsible for the crystallization of white salts on the surface. According to Chu, the origin of this problem was found to be the use of lime at the time the painting was created. If kaolin is used, this phenomenon does not occur. However, white salt crystallization can also appear if brick walls are the base of the wall painting, although this does not happen if the walls are made of dried mud bricks.

Chu notes that the murals in Minzhao Temple in southern Beijing are painted on walls made of dried mud bricks, and they do not show any alkalinization. He reports that, as was done for the Yongle Palace murals, the alkalinization phenomenon can be avoided, even in the presence of brick walls, by nailing a binding of hemp fibers to the wall surface and then coating it with three layers of a mixture of sand, earth, and stove ashes.[4]

According to Yu (Yu Feian, Silbergeld, and McNair 1988), during the Yuan dynasty, the painting style changed and ink painting was practiced. However, Yu emphasizes that brightly colored painting was still very much in use. In his discussion of pigments, he describes the proper method for the use of malachite. He recommends using the best-quality malachite and washing, grinding, and then separating it into five grades. After this a clear solution of glue must be added. First-grade green malachite is too coarse, but all the other grades are useful. Yu based his views on those found in the manual of bamboo painting by Li Kan (2000) that dates to the Yuan dynasty.

Apart from Malenka and Price (1997) and Yu Feian, Silbergeld, and McNair (1988), the survey did not clarify the type of binding media used for pigment application. Some differences were found in the composition of the preparation layer; clay mixed with sand and kaolin are both mentioned. For the coarse render used to prepare the walls for painting, the survey showed the common use of clay, sand, and loess with the addition of vegetable fibers. The wet-wall (Lu Hongnian 1956) and dry-wall (Chu Qi'en 2000) painting techniques deserve further investigation.

Sample Analysis

Ten samples of the Yao Wang Shan temple wall paintings were submitted to a complement of analytical methods, which are summarized in table 1. Nine of the samples came from the east wall. Two of those samples, YW1 and YW1', were collected from the same location on the mural: YW1 was used to determine the composition of the renders; YW1', to evaluate the presence and concentration of soluble salt. Only one sample (YW8) was taken from the west wall, to compare its composition with that of sample YW6 from the east wall.

The samples were analyzed with the following techniques: optical microscopy (OM),[5] polarized light microscopy (PLM), scanning electron microscopy (SEM) coupled with electron probe microanalysis (EPMA),[6] X-ray diffraction (XRD),[7] Fourier transform infrared spectroscopy (FTIR), Fourier transform infrared microscopy (μFTIR) coupled with attenuated total reflectance spectroscopy (ATR),[8] pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS),[9] gas chromatography–mass spectrometry (GC-MS),[10] differential thermal analysis (DTA),[11] Raman microspectroscopy (μRaman),[12] and ion chromatography (IC).[13]

Table 1 Mural Samples from Yao Wang Shan Temple

Sample	Color	Location	Analytical Method[a]
YW1	Grayish/white	East wall	OM, PLM, SEM/EPMA, DTA, XRD, IC
YW1'	Grayish/white	East wall	OM, SEM/EPMA
YW2	Green	East wall, near window	OM, SEM/EPMA, Py-GC-MS, GC-MS, μFTIR/ATR, μRaman
YW2'	Pale blue	East wall, near window	OM, SEM/EPMA, Py-GC-MS
YW3	Black	East wall, near window	OM, SEM/EPMA, Py-GC-MS, μFTIR/ATR
YW4	Red	East wall, Emperor's robe	OM, SEM/EPMA, Py-GC-MS, GC-MS
YW5	White	East wall, Emperor's robe	OM, SEM/EPMA, Py-GC-MS
YW6	Blue	East wall, Emperor's robe	OM, SEM/EPMA, Py-GC-MS, μFTIR/ATR
YW7	Salt efflorescence	East wall, lower part	IC
YW8	Blue	West wall, near window	OM, SEM/EPMA, Py-GC-MS, GC-MS, μFTIR/ATR

[a] Analytical methods:
SEM/EPMA = scanning electron microscopy coupled with electron probe microanalysis
OM = optical microscopy
PLM = polarized light microscopy
DTA = differential thermal analysis
XRD = X-ray diffraction
IC = ion chromatography
Py-GC-MS = pyrolysis gas chromatography–mass spectrometry
GC-MS = gas chromatography–mass–spectrometry
μFTIR/ATR = Fourier transform infrared microscopy coupled with attenuated total reflectance spectroscopy
μRaman = Raman microspectroscopy

Results

Renders and Preparation Layer

Table 2 summarizes the analytical results for the renders and preparation layer. The Yao Wang Shan murals are painted over a wall made of compressed-earth bricks. A coarse render followed by a finer one was applied before the application of a white preparation layer over which the painting was executed. The presence in the coarse render of hemp fibers and bamboo slivers is clearly detectable by the naked eye, as well as under stereomicroscopy and cross-section observations.

PLM examination of sample YW1 showed the presence in the coarse render of sand, silt, and clay. This same composition was also found in the fine render, along with micritic, bioclastic crystalline limestone and shell fragments, together with *coccio pesto*,[14] plagioclase, and quartz (fig. 2). XRD examination of the three main components of the renders (sand, silt, and clay) showed the presence of kaolinite and illite, together with a large amount of quartz, calcite, and plagioclase. Gypsum is also present.

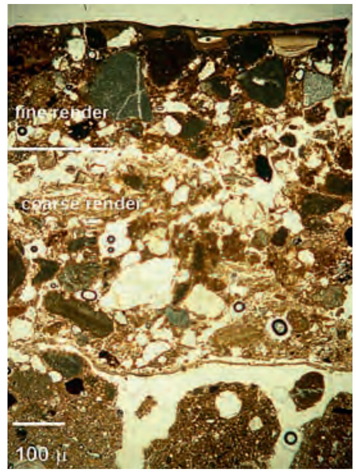


FIGURE 2 Thin section of sample YW1 viewed in transmitted light.

IC analyses of sample YW1' determined the presence of a fairly large amount of soluble sulfates (3.73%) in the renders, with low concentrations of chloride (0.07%) and nitrate (0.66%). (The low amount of chloride is discussed below, in reference to the possible source of the green pigments.) The same IC results were obtained from the salt efflorescence collected from the surface of the east wall (sample YW7), although in this case the increased sulfate concentration (4.65%) can be associated with the deposition of wind-borne gypsum particles deposited on the surface of the mural.

SEM/EPMA analyses showed that the white preparation layer consists of a fine white clay (illite and kaolinite) with some quartz, feldspar, and needle-like gypsum (fig. 3), with increasing concentration toward the surface of the mural. The iso-oriented morphology of the preparation layer probably indicates that the surface was smoothed before painting.

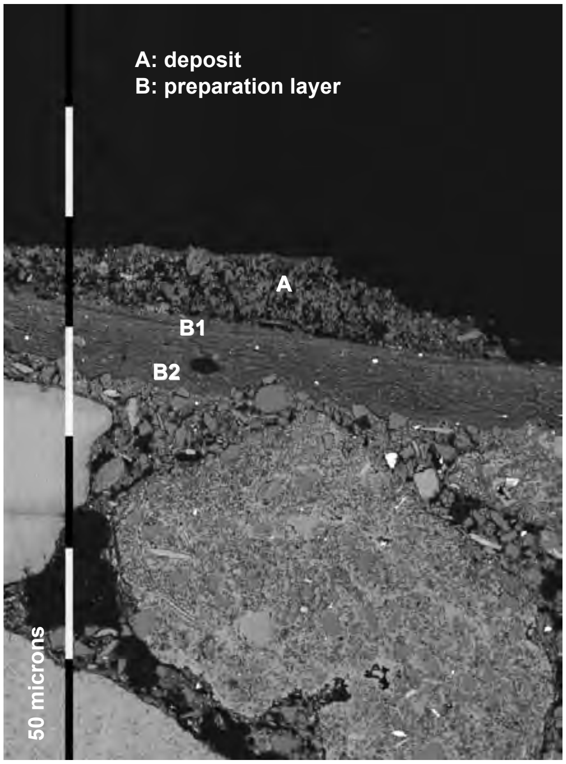
Paint Layers

Table 3 summarizes the paint palette used for the Yao Wang Shan temple murals. Analysis of cross-sectioned samples

Table 2 Analytical Results for Renders and Preparation Layer of the Yao Wang Shan Temple Murals

Sample	Layer	Identified Compounds	Other Compounds	Identification Method[a]
YW1	Preparation	Illite, kaolinite, quartz, feldspar	Gypsum	PLM, XRD, IC, SEM/EPMA
	Fine render	Sand, silt, clay	Micritic and bioclastic crystalline limestone, shell fragments, *coccio pesto*, plagioclase, quartz	
	Coarse render	Sand, silt, clay	Hemp fibers, bamboo slivers, kaolinite, illite, quartz, calcite, plagioclase, gypsum, sulfates, chlorides, nitrates	
YW1'	Same as YW1	Sulfates, chlorides, nitrates		IC
YW7	Salt efflorescence	Sulfates, chlorides, nitrates		IC

[a] Identification methods:
PLM = polarized light microscopy
XRD = X-ray diffraction
IC = ion chromatography
SEM/EPMA = scanning electron microscopy coupled with electron probe microanalysis



	% Si	% Al	% Ca	% K	% S	% Fe	% Ti
A°	28.8	10.7	28.8	4.0	20.1	6.9	
B1*	17.2	12.9	38.0	5.19	25.3	1.24	
B2*	37.8	25.3	16.6	12.8	4.6	1.54	1.34

° Micritic limestone + fine needle-like gypsum
* Fine clay (illite-kaolinite) + quartz, feldspar + needle-like gypsum

FIGURE 3 Results of SEM/EPMA analyses of the preparation layer in sample YW1.

Table 3 Paint Palette of Yao Wang Shan Temple Murals

Sample	Paint Color	Pigment Identification	Other Compounds	Identification Method[a]
YW2	green	atacamite	gypsum, whewellite, china clay, calcium nitrate, Paraloid B72, siccative oil, pine tree resin	SEM/EPMA, FTIR, µFTIR/ATR, µRaman, GC-MS, Py-GC-MS
YW2'	pale blue	lead white, azurite	Paraloid B72, siccative oil, pine tree resin	SEM/EPMA, Py-GC-MS
	deep blue	azurite, calcite, china clay		
YW3	black	ink	gypsum, whewellite, calcite, china clay,	SEM/EPMA, µFTIR/ATR,
	light green	lead white, atacamite, azurite	Paraloid B72, siccative oil, pine tree resin	Py-GC-MS, GC-MS
YW4	red	vermilion	Paraloid B72, siccative oil, pine tree resin	SEM/EPMA, Py-GC-MS, GC-MS
	orange	red lead		
	red	vermilion		
YW5	white	lead white	Paraloid B72	SEM/EPMA, Py-GC-MS
YW6	blue	azurite	gypsum, whewellite, Paraloid B72	SEM/EPMA, µFTIR/ATR, FTIR, Py-GC-MS
	white	china clay		
	blue	azurite		
YW8	blue	azurite	gypsum, whewellite, china clay, oleic acid, pine tree resin	SEM/EPMA, µFTIR/ATR, FTIR, Py-GC-MS, GC-MS

[a] Analytical techniques:
SEM/EPMA = scanning electron microscopy coupled with electron probe microanalysis
FTIR = Fourier transform infrared spectroscopy
µFTIR/ATR = Fourier transform infrared microscopy coupled with attenuated total reflectance spectroscopy
µRAMAN = Raman microspectroscopy
GC-MS = gas chromatography–mass spectrometry
Py-GC-MS = pyrolysis gas chromatography–mass spectrometry

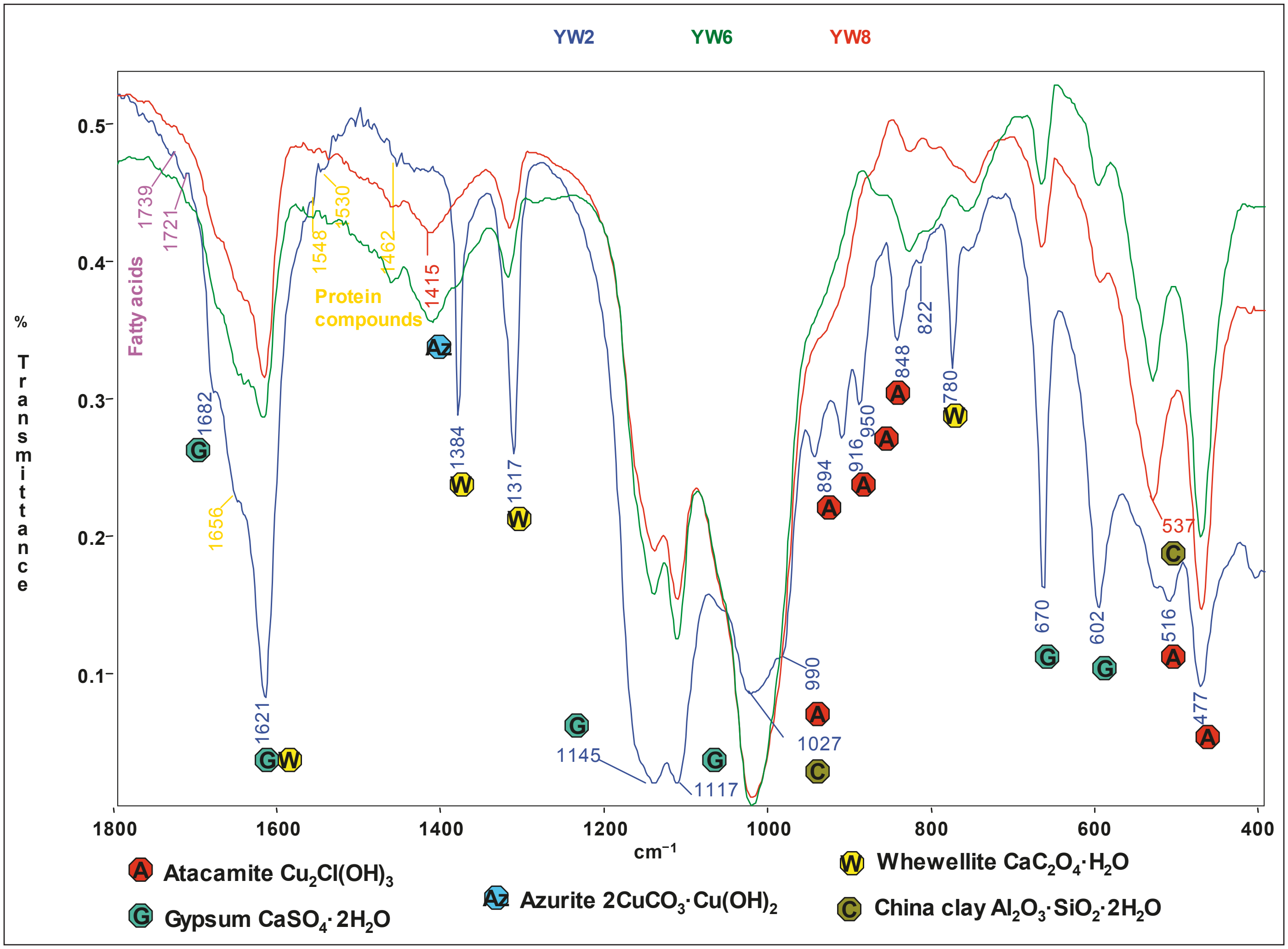


FIGURE 4 FTIR spectra at 2000–400 cm⁻¹ for samples YW2, YW6, and YW8.

revealed that in some cases more than one paint layer was applied to achieve a given color tonality. For example, in sample YW4 an orange paint layer (red lead) was applied between two red paint layers (vermilion) to yield a warm tone; and in sample YW6 a white paint layer (white clay) was used between two blue paint layers (azurite) to achieve a lighter tone. Different tonalities were also achieved by mixing pigments, such as the pale blue tones that were obtained by mixing azurite with lead white (sample YW2'); for deeper tones, only azurite was used (sample YW8). Lead white was used to color white areas (sample YW5).

FTIR performed on bulk paint samples (YW2, YW6, YW8) identified the presence of other inorganic compounds, such as gypsum, calcite, and whewellite (hydrated calcium oxalate, $CaC_2O_4 \cdot H_2O$) (fig. 4). This analysis confirmed the elemental composition of the samples obtained from the SEM/EPMA analysis. The FTIR spectrum of sample YW2 also showed weak bands at 1462, 1530, 1548, and 1656 cm^{-1} as well as at 1721 and 1739 cm^{-1}, and these bands are associated with the presence of proteinaceous and fatty acid materials.

Particular attention is directed to the green pigments of samples YW2 and YW3 (in sample YW3 the green color is found underneath a black layer of ink).[15] Both paint samples are light colored when viewed in cross section, and they contain rounded green particles with an average diameter of 10 μm. Copper and chlorine are the main chemical constituents of the particles. EPMA analyses performed on a single particle revealed that the copper concentration decreases from the center outward, while the chlorine concentration increases (fig. 5). Both μRaman and μFTIR/ATR analyses

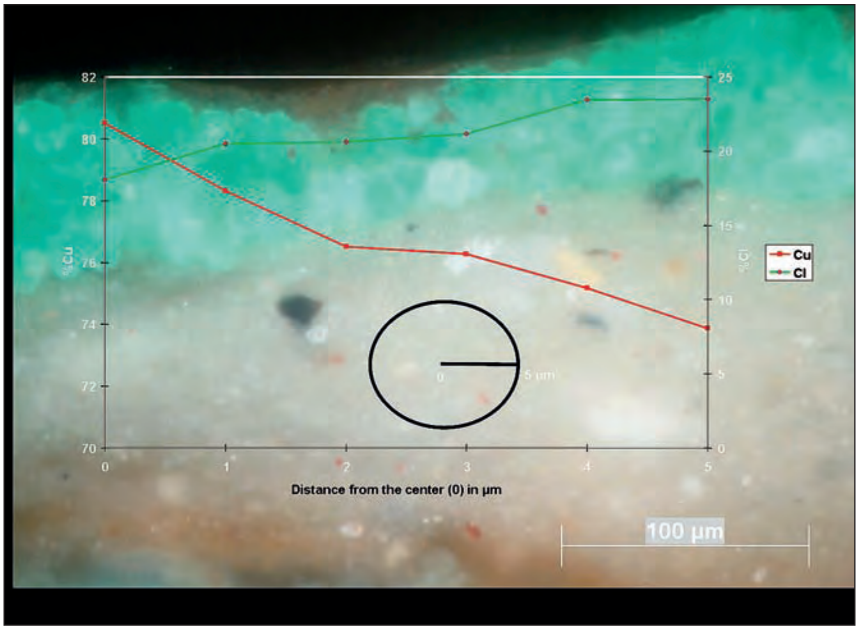


FIGURE 5 Cross-section photomicrograph (background) of rounded particles of green atacamite pigment in sample YW2. Superimposed is an EPMA-obtained profile of the copper and chlorine concentration distribution within a single particle.

performed directly on the cross-sectioned samples confirmed the green pigment is atacamite. Lead white was also detected mixed with atacamite and azurite in sample YW3, imparting an even lighter tonality.

Binding Media

In all samples, the Py-GC-MS analyses performed in both normal and derivatization conditions indicate the presence of Paraloid® B72, an ethyl methacrylate copolymer applied by Chinese conservators two years ago to partially preconsolidate the paint surface (fig. 6).

High concentrations of the dimethyl ester of azelaic acid (nonanedioic acid) that were detected are evidence of a siccative (drying) oil in samples YW2' and YW3. Although this acid is commonly found in old and therefore degraded siccative oils analyzed with Py-GC-MS in TMAH derivatization conditions, it is not possible to assign unambiguously the results to a specific siccative oil (Chiavari et al. 1993; Chiavari et al. 1995; Chiavari et al. 2002). In this case, however, the drying oil is most likely tung oil, obtained from the seeds of tung trees (*Aleurites fordii*, *A. cordata*, and *A. montana*) that are indigenous to the mountain regions of China. This assignment is further supported by historical information and by consideration of the fact that neither scientific nor historical evidence exists for the use of another type of siccative oil, such as linseed oil, in ancient China (Mazzeo et al. 2004). In *Tiangong kaiwu* (Exploiting the Works of Nature), a book written by Song Yingxing in the seventeenth century, specific reference is made to the use of tung oil mixed with lime for caulking ships or lining the inside of a well. In addition, Qi (1986) makes specific reference to the use of tung oil, mixed with brick powder, lime, flour, and pig blood, as priming material for painting wooden architectural decorations in the Qing dynasty (1644–1911).

Py-GC-MS analyses identified a pine tree resin in samples YW2, YW2', YW3, and YW4 through its characteristic dehydroabietic acid marker. Because both Py-GC-MS and GC-MS analyses were performed on bulk samples, it is not possible to clarify where in the samples the natural resin is located stratigraphically. Nevertheless, microscope observation of cross-sectioned samples viewed under UV light showed the presence of a thin layer on top of the colors

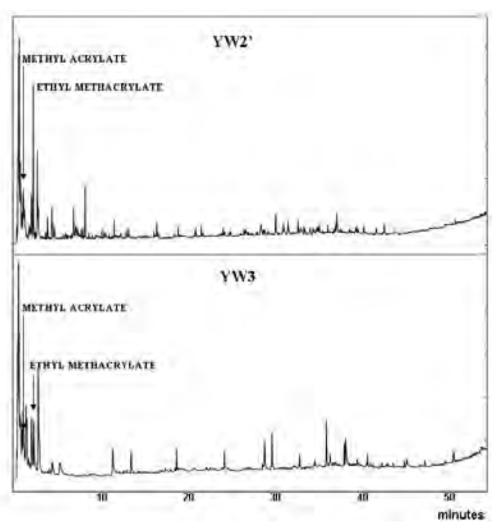


FIGURE 6 Py-GC-MS total ion chromatograms of samples YW2' and YW3, revealing the presence of ethyl methacrylate (Paraloid® B72) in normal conditions.

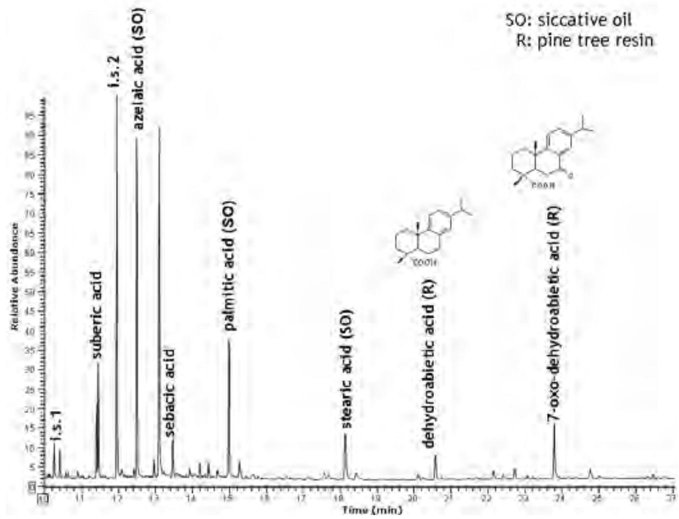


FIGURE 7 GC-MS total ion chromatograms of sample YW4. All acids are in the form of TMS esters.

that fluoresces orange-yellow and can be associated with the presence of a varnish.

In sample YW4, GC-MS analyses (Colombini et al. 2003; Colombini et al. 2004) were negative for protein, apart from a minor amount of glycine detected (0.3% w/w). In general, the gas chromatogram shows a different protein profile if compared with those commonly found in proteinaceous materials. Therefore, the presence of an animal glue used as a binding material can be excluded.

The presence of both a siccative oil (binding medium) and a pine tree resin (varnish) was confirmed through GC-MS analyses of samples YW2, YW4, and YW8 (fig. 7). Nevertheless, the palmitic/stearic acid ratio was not uniform in all samples, ranging from 0.8 (YW2) to 3.4 (YW4), with a very low azelaic acid content in sample YW8, where oleic acid and C15 and C17 fatty acids were also detected. Since the oleic acid is not a component of siccative oil, it may have an animal origin.

Further evidence that a siccative oil was used as a binding medium is found in sample YW4. Microscope observation of a cross section of this sample viewed under UV light shows that both the preparation layer and the red paint layer fluoresce yellow.

Results Database

The results obtained from the different analytical techniques used to characterize the Yao Wang Shan mural paintings are compiled in the Diagnostic Data Archiving System (DIDARS) database. Sample pages from this database are shown in figure 8. The database was developed by one of the authors as part of a UNESCO-DPRK Funds in Trust project (Mazzeo 2005).[16]

The database is a useful archiving tool, especially for compiling results from many different analytical techniques, making it possible for researchers to share results online with participating laboratories. User-friendly, the database is accessible to a range of interested individuals, including conservation scientists, conservator-restorers, archaeologists, and art historians.

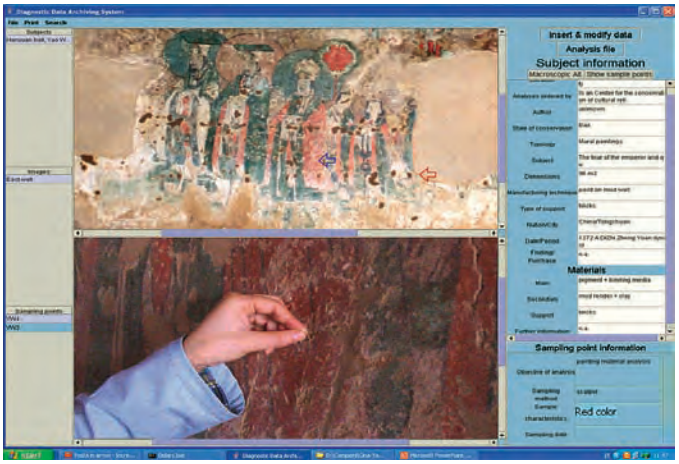
Discussion

The analytical results regarding the paint palette and original preparation technique of the Yao Wang Shan mural paintings are in good agreement with the literature survey results. Furthermore, the morphology of these murals is stratigraphically similar to that of other Yuan dynasty wall paintings exhibited in the Philadelphia Museum of Art (Malenka and Price 1997).

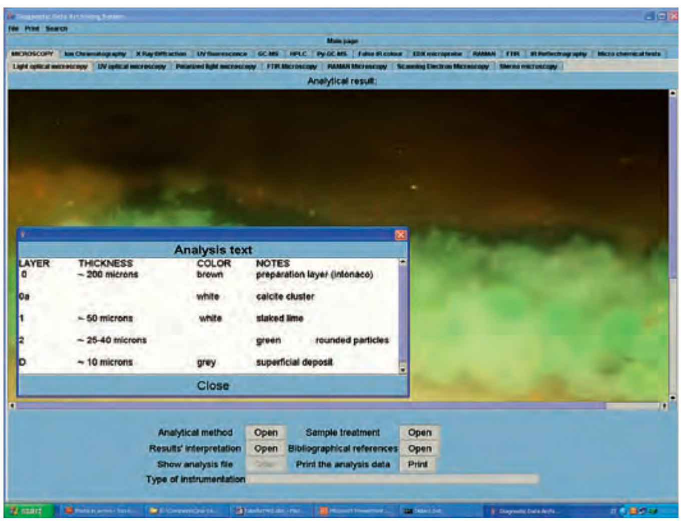
The fine white preparation layer was applied over the fine and coarse renders and then smoothed while still wet (Lu Hongnian 1956), a practice that is common to other far East Asian mural paintings (Mazzeo et al. 2004). There is no evidence that colors were applied while the preparation layer was still wet, as analysis of cross sections of samples from the paintings reveal the presence of a discontinuity between the two layers.

Even though the paint palette is restricted to a few colors, some paints were applied in multiple layers as well as in a mixture of pigments to lighten or deepen their tonality, such as for the blues in samples YW2' and YW6 and red in sample YW4. Analyses confirm the presence of a green pigment based on copper hydroxyl chloride compounds (Piqué 1992; Godfraind 2000). Because of the particular rounded shape of the pigment particles and the very low concentration of chlorine detected by IC in the renders, we favor a synthetic origin for this pigment rather than a natural alteration of malachite.

Three kinds of organic materials (siccative oil, conifer resin, and proteinaceous material) were detected in the murals, although their identification was complicated by the Paraloid® B72 that had been applied to the paintings during a previous conservation effort. The amount of proteinaceous material in the samples was very low compared with the



(a)



(b)

FIGURE 8 Sample pages from the DIDARS database showing (a) detail from the Yao Wang Shan mural paintings and (b) related sampling information.

amount of siccative oil (probably tung oil) detected. This suggests that an oil painting technique was used to create the murals rather than a tempera (glue) technique.

A pine tree resin appears to have been applied as a varnish on the wall paintings. The dark brown appearance of some parts of the murals (see fig. 1) where samples containing the natural resin were collected may be associated with degraded resin.

Conclusion

The literature survey has shown how important it is for conservation scientists to search for historical information when conducting scientific examinations of Chinese mural paintings. In the case of the Yao Wang Shan murals, the scientific results for the materials used to prepare the walls are in good agreement with the information collected through the literature survey.

On the other hand, except for what Yu (Yu Feian, Silbergeld, and McNair 1988) mentions about pigment, none of the surveyed Chinese publications make specific reference to binding materials or the use of varnish finishes. In particular, the finding of a siccative oil used as a binding medium in the Yao Wang murals is reported here for the first time. This finding points out the need to continue searching for more historical information to improve the interpretation and reliability of our understanding of the materials and techniques used in Yuan dynasty wall paintings.

Acknowledgments

The authors express their gratitude to the Shaanxi Cultural Relics Bureau in Xi'an, China, and the Xi'an Center for the Conservation and Restoration of Cultural Relics for providing samples of the Yao Wang Shan mural paintings. We also extend thanks to Pietro Baraldi, Department of Chemistry, University of Modena, for the Raman analyses; to Sonia Casolari, Department of Chemistry, University of Bologna, for the ion chromatography analyses; and to Sara Piombo, who worked on this project for her bachelor's degree thesis.

Notes

1 Yao Wang Shan was the home of Sun Simiao from about 581 to 682 C.E., during the Sui and Tang dynasties. Called the "King of Medicine," Sun Simiao is well known throughout China for his studies of acupuncture and herbal medicine.

2 Apart from the murals at Dunhuang and those at Yao Wang Shan, similar paintings have been removed from their original locations, with the resulting contamination of the original constituent painting materials. For example, the thirteenth-century Yongle Temple in Shanxi province had been completely rebuilt at a different location in 1959 to avoid being flooded during construction of irrigation works at the original site. Some of the iconography in the paintings of Yongle Temple are similar to the *chaoyuantu* in the Yao Wang temple. However, because of this relocation, the paint layers are no longer a

reliable reference with which to study Yuan dynasty painting techniques.

3 The original Chinese word means "yellow ocher," but it actually refers to the local loess, a buff to yellowish brown loamy deposit.

4 In *Yingzao fashi* (1925), a book of architecture from the Song dynasty (960–1279), the use of clay (11.5%), white clay (11.5%), and sand (11.5%) mixed with macerated hemp (64%) and raw hemp (1.3%) is mentioned for the wall surface preparation.

5 Samples were embedded in a resin support, then cross-sectioned and polished according to the conventional method. Dark field observation of cross-sectioned samples was performed using an optical microscope (Olympus BX51M). Photomicrographs were recorded with a scanning digital camera (Olympus DP70).

6 A scanning electron microscope equipped with an energy dispersive X-ray analyzer (Philips XL 20 model SEM-EDX) was used on the same cross-sectioned samples already prepared for the optical microscopy observations. The elemental composition was determined using an acceleration voltage of 25–30 KeV, lifetime > 50 sec, CPS ≈ 2000, and working distance 34 mm. EDX-4 software equipped with a ZAF correction procedure for bulk specimens was used for semiquantitative analyses of the collected X-ray intensities.

7 A Philips PV 1710 with a Cu-K radiation, 40 kV, and 40 mA, Ni filter radiation was used. Diffraction patterns were interpreted by comparison with data from the Joint Committee for Powder Diffraction Standards.

8 FTIR analyses were performed on both bulk and cross-sectioned samples. The KBr pellet technique was used for bulk analyses, and spectra were recorded in transmission mode. Cross-sectioned sample analyses were performed by placing samples directly on the stage of a Thermo Nicolet Continuum FTIR microscope and analyzing each paint layer with the slide-on micro ATR (Si crystal) device in reflection mode.

9 Analytical pyrolysis experiments were performed using an integrated system consisting of a CDS Pyroprobe 1000 heated filament pyrolyzer (Chemical Data System, Oxford, Pa., USA) and a Varian 3400 gas chromatograph coupled to a Saturn II ion-trap mass spectrometer (Varian Analytical Instruments, Walnut Creek, Calif., USA). A DB-5MS J&W capillary column (30 m × 0.25 mm i.d.; 0.25 µ film thickness) was programmed from 50°C to 300°C at 5°C min^{-1}, holding the initial temperature for 2 minutes. The samples, less than 1 mg, were pyrolyzed without treatment in duplicate through a quartz sample holder at 700°C for 10 seconds. The pyrolysis experiments were carried out in methylating conditions adding 5 µl of an aqueous solution of 25% of tetramethylammonium hydroxide (TMAH) to the sample before pyrolysis; in this way, methylation of carboxylic and hydroxyl groups was achieved. The Py-GC interface and the injection port were kept at 250°C. Injection mode was split (1:50 split ratio). The carrier gas was helium at a flow rate of 1.5 ml min^{-1}. Mass spectra (1 scan sec^{-1}) were recorded under electron impact at 70 eV from 40 to 450 m/z.

10 A GC-MS system made up of a 5890 2A gas-chromatograph (Hewlett-Packard-USA) equipped with an on-column injection port and a quadrupole mass spectrometer detector (model 5971A) was used to separate and identify the organic compounds. Chromatographic separation was performed on a chemically bonded fused silica capillary column HP-5MS (i.d. 0.25 mm, length 30 m) with a 2 m deactivated silica precolumn. GC conditions for amino acids were as follows: initial temperature 100°C, 2 min isothermal, 6°C min^{-1} up to 280°C, 15 min isothermal. Carrier gas: He, constant flow 1.2 ml min^{-1}. GC conditions for fatty acids, terpenic compounds, and nonsaponifiable fraction: initial temperature 80°C, 2 min isothermal, 10°C min^{-1} up to 200°C, 6°C min^{-1} up to 280°C, 8 min isothermal. Carrier gas: He, constant flow 1.3 ml min^{-1}. Samples (0.1–0.5 mg) were subjected to ammonia extraction and acid hydrolysis using microwaves. The acidic hydrolyzate was extracted with diethyl ether, and the extract was added to the residue from the ammonia extraction and, after drying, saponified and analyzed by GC-MS for the determination of terpenic species, fatty acids, and sterol content after derivatization with BSTFA (bis-(trimethylsilyl) trifluoroacetamide). The residual acidic hydrolizate was analyzed by GC-MS after derivatization with MTBSTFA (N-(t-butyldimethylsilyl)-N-methyltrifluoroacetamide). Quantitative amino acid analysis was performed by using the GC-MS in single ion monitoring (SIM) mode.

11 A SETARAM TAG 24 apparatus was used with a heating speed of 20°C min^{-1}, under a CO_2 flux, and temperature range from 20°C to 1,000°C.

12 Raman microspectroscopy of the paint samples was performed by placing the cross-sectioned samples on the microscope stage and directing the laser light through a 50x objective of an Olympus microscope onto the different paint layers visible under cross section. The Raman analyses were carried out with a micro-Raman Labram and a laser at 632.8 nm, at a power ranging from 0.5 to 5 mW (slit: 5 cm^{-1}), according to the sensitivity of the compounds to be investigated. A CCD (330 × 1,100 pixels) detector cooled by the Peltier effect at 200 K was used.

13 A Dionex DX 100 was used with a conductibility detector.

14 *Coccio pesto* is material consisting of crushed, dehydrated earthenware. It is obtained by pulverizing clay materials, such as bricks and roofing tiles, that are then baked at low temperature (900°C). The addition of *coccio pesto* to plasters confers waterproofing properties.

15 Not enough sample was available to identify the composition of the ink.

16 The project was titled "Preservation of Cultural Heritage in the Democratic People's Republic of Korea, notably the Yaksuri Tomb and Capacity Building at the Korean Cultural Preservation Centre, DPRK."

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Documentation and Emergency Treatment of Wall Paintings in the Chamba Lakhang (Maitreya Temple): Developing a Methodology to Conserve Mural Paintings in India's Ladakh District

Sanjay Dhar

Abstract: *India's Ladakh district is located in the Himalayan region of the state of Jammu and Kashmir. It is home to a large number of monasteries of various denominations of lamaistic Buddhism that have remained insular during the past two centuries for geopolitical reasons. Over the past two decades, as a result of growing interest in the region's artistic and cultural heritage, conservation efforts have been undertaken aimed at monuments of historic, religious, and cultural significance. However, not all these efforts have been conducted in a scientific manner. In the absence of a monitoring mechanism and clearly formulated norms and methodologies, it is difficult to regulate the quality of the interventions. Against this backdrop, the documentation and emergency treatment of wall paintings in the sixteenth-century Chamba Lakhang (also known as the Maitreya temple) in the village of Basgo, the first capital of the Namgyal dynasty, establishes a paradigm for future restoration projects in the region.*

This paper details the documentation and emergency treatment of the wall paintings in the Chamba Lakhang and reports the manner in which local community participation and sustained efforts by individuals and organizations over the past six years ensured a multidisciplinary approach involving the architectural conservator, soil specialists, structural engineers, and paintings conservators. This approach builds a matrix for traditional conservation methodology and expertise through community participation and scientific conservation techniques. The heritage preservation model so developed complies with international guidelines and has as its ultimate aim the creation of local human resources for the preservation of the tangible and intangible heritage of the region.

Conservation and restoration of wall paintings is a difficult process, owing not only to the varied physical requirements of the building and its micro-environment but also to its social environment. This effort becomes more daunting in the context of developing countries. In India, for instance, with the sheer number of monuments of historic, religious, and cultural significance, the government is barely able to manage a small percentage of the most important sites; and few organizations in the nongovernmental (not-for-profit) and private sectors are equipped to deal with the totality of the complexities of conservation and restoration.

In large parts of India, as a result of overprotection and lack of communication between the authorities and the community, conservation is seen as antidevelopment. There is also the element of devotion and the desire to offer the best to the gods, which leads religious communities to take down damaged sections of structures and rebuild. This approach results from a lack of information about the potential of conservation. More often than not, help for many monuments never arrives due to uninformed authorities or a lack of funds and trained personnel. Add to this scenario a large number of untrained dilettantes, both national and international, working in developing countries, who manage to raise funds for some projects and then leave the sites in worse condition, creating suspicion and mistrust within the community and thus affecting future work in the area.

In 2000 the Namgyal Institute for Research in Ladakhi Art and Culture (NIRLAC) received funding for the documentation and condition assessment of the wall paintings in the Chamba Lakhang (also known as the Maitreya temple) at Basgo, a village located in the Ladakh district, also referred to as Western Tibet, in the Himalayan region of the North Indian state of Jammu and Kashmir.[1] The Ladakh district is home to a large number of monasteries of various denominations of lamaistic Buddhism that have remained insular during the past two centuries for geopolitical reasons.[2]

The Chamba Lakhang project gained considerable attention when the Basgo Welfare Committee, the main forum for enabling various social, economic, and educational activities at the village level, raised funds to maintain and care for the monument. At the same time, the committee had an enlightened patron who was able to steer the community away from random reconstruction. Support from NIRLAC and other individuals resulted in the Basgo site being nominated to the World Monuments Watch List of 100 most endangered sites. It was against this backdrop that the project coordination team from NIRLAC, comprising the project coordinator, architectural and paintings consultants, and a member of the village committee, felt that the Chamba Lakhang at Basgo could be used to demonstrate the benefits of conservation in Ladakh and also to develop a benchmark for future projects in the area.

The village of Basgo is located about 35 kilometers west of Leh, the capital of Ladakh. Basgo was the first capital of the Namgyal dynasty, and today the site has the remains of the royal palace, the houses of ministers and nobles, and three temples dedicated to Maitreya located within the remains of the citadel walls, which were fortified with bastions, some of which survive. The largest of the extant historic structures at Basgo is the temple known as the Chamba Lakhang (*Chamba* is the Ladhaki word for Maitreya, the Future Buddha; *lakhang* means "prayer hall"), which was built in the sixteenth century by Tsewang Namgyal. The temple is located on a hill surrounded by a mountain on three sides; the present village of Basgo is located at its base. The main assembly hall of the temple measures approximately 9.6 by 9 meters and is 5.4 meters high. It is flanked on both sides by a stairwell and small rooms that are the residence of the lamas. Originally the temple had another floor over the main hall, but this was demolished during previous repairs, and now only the facade of the second floor survives. There is an additional floor enclosing the bust of Maitreya, with a small window through which he supposedly watches over Basgo, warding off evil and bringing good fortune to the villagers.

On entering the main hall of the temple, one is confronted by a colossal sculpture of Maitreya, but only the legs and part of the bust are visible from the entrance. As one approaches and looks up, the entire sculpture can be seen. Maitreya is seated on a throne with hands in what is called the "turning the wheel of Dharma" position. On both sides of the pedestal on which Maitreya is seated are the life-size statues of the bodhisattvas Avalokitesvara Padmapani (holding a lotus) and Vajrapani (holding a thunderbolt).

Three walls in the main hall are covered with paintings. The hall has four slender painted pillars, and the ceiling, covered by wooden slats over horizontal support structures (purlins), is also painted with beautiful geometric and figurative designs.

The temple is owned by the Hemis Monastery (the Red Hat sect of Buddhism), which posts a lama who performs rituals and daily prayers at the temple and also looks after the ceremonial and spiritual needs of the villagers.

Chamba Lakhang Wall Paintings

The wall paintings at the Chamba Lakhang stand apart for their beauty and simplicity of execution. The colors, deep and rich against a light blue and green background, provide a profound experience for the viewer. The effect is that of entering a mandala (a Buddhist geometrical design meant for meditation) depicting the paradise of Maitreya and his accompanying deities. The artist has also achieved a distinctive style that marks the beginnings of the Ladakhi style in painting.

On the panel over the entrance is a depiction of the bodhisattva Vajrapani, and on either side are depicted deities known as the Four Heavenly Kings. Flanking Vajrapani on both sides are depictions of Tara, a Buddhist goddess traditionally shown in green and white forms.[3]

On the right-hand wall of the temple are three Dhyani Buddhas and Tsong-khapa (founder of the Gelugpa, or Yellow Hat, sect of Buddhism), and on the left-hand side is an image of one Dhyani Buddha and a Vajrapani. The other two panels, which depict Padma Karpo (an esteemed teacher of Vajrayana Buddhism) and Avalokitesvara, were repainted some sixty years ago. These are different stylistically from the rest of the paintings.

A register runs along the lower part of the wall painting, about 1.5 meters from the floor, that has scenes depicting the life of Buddha. In one part of the register there is a depiction of the Namgyal ruler who commissioned the temple, along with his family. The lines in the painting are delicate despite its large size. Though it appears to be rendered in panels, the painting has a unified appearance that gives it a unique character. At the top of the walls there is a pattern of painted cloth that imitates the veil that covers the deity during the night to prevent the evil eye from falling on it.

Nature of the Damage to the Chamba Lakhang

The first time I entered the Chamba Lakhang, I was struck by the quality and intensity of colors. In most other painted chambers in Ladakh, the walls are completely covered with soot, and the paintings can barely be discerned. However, at the Chamba Lakhang, the intensity and the quality of paintings were clear, despite the major structural cracks through most of the panels. The figures in the paintings were also damaged from water seepage, and dried mud encrusted large portions. On closer examination, though the losses seemed limited, the delamination in the plaster, visible around the major cracks, was worrisome. Further, I was shown small fragments of painted plaster that had fallen to the ground. The main columns in the hall were out of plumb and had been supported with additional props; repairs to the roof around the areas of water seepage had damaged the plaster near the beam ends. Despite the damage, mostly of a mechanical nature, the walls appeared to be in good condition.

The present condition of the Chamba Lakhang is testimony to the people of Basgo, who over the years took prompt action to impede deterioration. In the recent past, the Basgo Welfare Committee undertook several measures to ensure that the conservation process would be systematic and scientific. It is a result of this informed approach that a significant part of the paintings have survived in their original condition.

Scientific Examination of the Chamba Lakhang

In order to develop an effective overall conservation strategy for the damaged wall paintings in the Chamba Lakhang, the following studies and tests were commissioned:

1. Detailed architectural drawings and condition assessment of the structure.
2. Geological survey of the stone and soil of the hill on which the temple is located.
3. Contour mapping of the surrounding area up to 100 meters, for a better understanding of water drainage in and around the site, as well as for developing the site map and future planning.
4. Detailed analysis of the mud and mortar samples used in the construction of the Chamba Lakhang and some of the structures in the citadel, specifically, the surviving bastion walls.
5. Detailed analysis of soil samples taken from the vicinity of the site and of the traditional building materials used in the region, to determine the best clay mixtures at the time of conservation.
6. Stratigraphic study of the paint layer and mud plaster.
7. Examination of the paint layer in ultraviolet light.
8. Microscopic analysis of surface patterns (brushstrokes, etc.) of the paint layer to understand the process of paint application and the artist's deliberate play with textures and effects and to determine the nature of deposits on the paint surface.
9. Study of cracks and crevices in the walls to ascertain insect and other biological activity, as well as the layering and deterioration within, using an auriscope (otoscope).
10. Establishment of safety parameters for the use of chemicals and solvents to clean the pictorial surface.
11. Analysis of the properties of the mud bricks used in the wall to determine water absorption rate, clay adhesion, and so on, for the purpose of developing the materials and methodology for conservation.
12. Correlation of the condition of the paintings with the architectural assessment of structural and building-related problems. This was done by superimposing the architectural assessment drawings over the graphic documentation of the wall paintings. This was important for developing a combined strategy for the conservation of the paintings and the structure of the temple.

Causes of Deterioration

The primary causes of deterioration of the paintings in the Chamba Lakhang are water, foundation shift, wind, and human activities.

Water

Most of the disfigurement of the painted surface was due to rainwater seepage. It is reported that this damage occurred over two days of continuous rain. Although the exact time is not clear, on the basis of oral accounts this must have happened at least 100 to 150 years ago. At that time the temple had been closed and left unattended, and the extent of the damage was only realized later, when it was opened. The damage was extensive, and two panels of the wall paintings were completely repainted. Today one can identify some of the surviving original paint layer in the repainted areas. The subject of this repainting is very different from what must have been there originally, as it is not in consonance with the original paintings. One of the repainted panels was again heavily damaged by water seepage; the exact time of this incident is also not clear (presumably about sixty years ago). It was obvious from our assessment that the roof over this wall had endemic problems that had been repaired several times, but the repairs seem to have always been insufficient.

As is well known, water is one of the strongest agents of deterioration, and mud-brick walls are particularly susceptible. Water moving down the walls during rains cuts into the plaster surface and washes away the water-soluble pigment. Also, water moving down the plaster surface leads to detachment between the various layers of the composite painting, creating areas of loss.

Foundation Shift

The Chamba Lakhang was built on the highest point of a hill, over soil composed of clay and mudstone. The underlying mudstone is extremely brittle and disintegrates into powder with little pressure. Until very recently, the temple's foundation rock was exposed and subjected to wind and snow erosion, which carved a furrow into the rock around the base. This furrow creates a micro-environment, trapping the passing wind and forcing it to circulate around the foundation. Loose particles of soil and sand act as abrasive, cutting into the foundation rock. As a result, portions under the temple walls have collapsed, causing shifts in the foundation, which then causes structural cracks in the walls. From local accounts, these cracks developed very early in the history of the temple. According to reports, no fresh cracks are developing, so it may be assumed that the building's foundation has achieved some sort of equilibrium.

Wind

It is unusual for wind to cause damage to paintings inside a closed structure. As an agent of deterioration inside the Chamba Lakhang, wind plays a subtle but important role. The walls of the temple are laid out in mud bricks, but the mortar is not spread sufficiently, leaving small gaps between the bricks. Due to structural movement, water seepage, frequent repairs, and changes to the ancillary structure, the plaster on the exterior of the painted walls has disintegrated in most places. Though only one of the three walls with paintings is exposed directly to the elements, several openings in the adjoining structures (stairwell and residence rooms) allow wind to enter the hall. When its velocity is high, wind enters through the small spaces and crevices in the wall and into the main chamber of the temple through structural cracks. As it tries to escape through these cracks, the wind picks up sand particles freed from the mortar between the bricks in the wall, and these particles act as an abrasive, slowly cutting into the ground around the cracks and detaching small pieces of the paint layer along the edges of the cracks.

Human Activities

At the Chamba Lakhang, human activities have caused some damage to the wall paintings. For example, until recently, the devotees at the temple made offerings of ghee (clarified butter), which was poured into lamps that were kept burning all the time, depositing soot over the paintings. In recent years, however, the lamps have been lit in specially designed metal cupboards with a chimney and placed outside the main hall to prevent soot deposition on the paintings. Touching has also abraded the lower regions of the paintings.

Preserving the Chamba Lakhang Wall Paintings

As a proviso to the issues addressed in this paper, it is emphasized that the strict guidelines and processes generally followed in the execution of conservation projects in the West are often compromised in projects in the East, such as at the Chamba Lakhang, because of lack of funds, materials, trained personnel, scientific study, and awareness. In this project we have tried to overcome these problems, within the limited resources available, to develop a sustainable model for the region. The documentation and emergency treatment of the wall paintings in the Chamba Lakhang were planned as a model for future conservation efforts in Ladakh, taking into account the specific conservation needs based on an assessment of past practices in the region. The proposed model is based on international conservation practice and adheres to the various guidelines, charters, and projects that have been accepted as standards in the practice of conservation internationally. We used the opportunity to document the paintings, to undertake much-needed emergency measures, and to develop a treatment methodology after extensive testing of materials and techniques. Most important, through a series of dialogues, on- and off-site, with all residents of Basgo, the concepts and problems of cleaning, reintegration of the pictorial surface, and ethics and norms of conservation were introduced to the local community.

Objectives for the Conservation Model

- To study the problems of deterioration of the wall paintings in the Chamba Lakhang.
- To record photographically the condition of the paintings to help in the proper assessment of the deterioration.
- To undertake basic experiments to understand the properties of materials used in the wall paintings.
- To undertake tests to establish the safety parameters of solvents for cleaning the paintings and to develop a safe methodology for cleaning the paint layer.
- To undertake emergency treatment in areas of potential loss.
- To explore local material resources and study logistical supply problems during the conservation process.
- To prepare cost estimates and a work schedule for conservation of the paintings in the Chamba Lakhang.
- To introduce the scientific concept of restoration to the local population and concerned authorities; to demonstrate what conservation entails through interaction with the local population while trying to understand their motivations and their expectations from the conservation process.

Anatomy of the Chamba Lakhang Wall Paintings

A detailed on-site study was carried out to fully understand the basic anatomy of the wall paintings and the technique used in their execution. The anatomy of the paintings is simple, as shown in figure 1:

- Wall: cast mud bricks in mud mortar.
- Ground: mud plaster mixed with vegetable fiber and grit and strengthened with a dilute animal glue solution.
- Priming (primer): kaolin mixed with animal glue.
- Paint layer: pigment mixed with animal glue. The paint layer comprises layers of various colors, which have been superimposed in some cases. The pigments that we were able to identify through analysis are yellow ocher, red ocher, lamp black, orpiment, and cinnabar. Gold leaf has also been applied, and the figures have been outlined in black or deep red to give definition to the drawings.
- Protective coating: shellac was applied in selected areas, mainly over the reds and yellows in the garments. The purpose seems to have been to saturate the color and give a feeling of richness to the painted fabric rather than to serve solely as a protective layer. Tests to identify this varnish as shellac could not be carried out. Its identification is based on empirical observation and its use in the surviving Tibetan painting tradition.

Painting Technique

In art historical literature, the Chamba Lakhang paintings are considered second only to those found in Alchi, an eleventh-century temple group located some 40 kilometers from Basgo and containing the most significant extant examples of the painting style from Kashmir. The stylistics of Indian painting are defined by the art in the Ajanta caves in western India (second century B.C.E.–seventh century C.E.), which are the earliest known paintings in the country. Although a thousand years separate the paintings in the Ajanta caves and those in the Chamba Lakhang at Basgo, the painting technique has remained virtually unchanged. The paintings in the Chamba Lakhang signify the return of a style, fully evolved, that emerged from India, traveled the

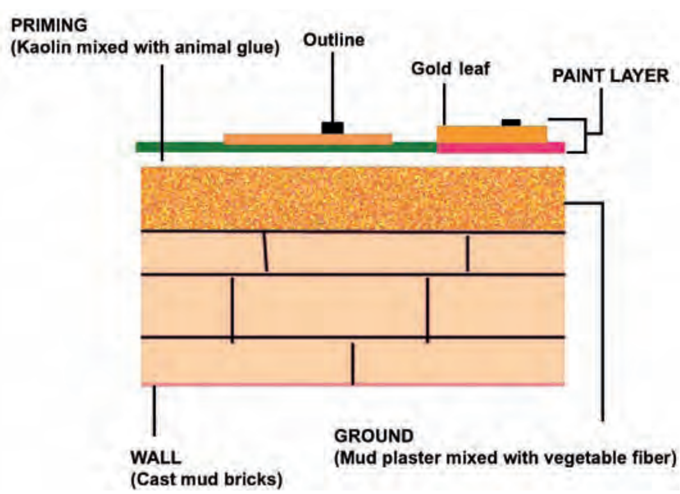

FIGURE 1 Schematic cross section showing the different layers making up the wall paintings in the Chamba Lakhang (Maitreya temple).

Silk Road, and gained from the artistic influences of other cultures, notably the Chinese in Tibet.

The painting technique used in the Chamba Lakhang conforms to the tenets of the seventh-century Indian canonical treatise on painting, the *Vishnudharmottara-Purana* (Shah 1958–61).[4] Similar texts are also available in the Mahayana tradition, adapted from early Hindu texts, which provide the iconographic and iconometric details of the deities to be painted, details about the painting technique, and instructions on how to prepare the painting materials.

Preparation. The walls of the Chamba Lakhang are of cast mud bricks carefully prepared for application of the ground. The ground comprises clay, properly modified with an additive of pounded vegetable fiber and sand. After this had partially dried, the surface was burnished. Some water may have been used at this stage, as a slight change in the texture of the clay can be seen. Initially, we assumed that this might be due to the application of a separate layer of fine mud plaster. But stratigraphic studies show that the smooth finish seems most likely to be a result of working the surface with a metallic object. At this stage, a dilute hot solution of animal glue in water was applied to the surface by throwing the solution at the prepared wall from a container kept warm on a coal stove (this practice is still in use). After the surface was bone dry, a layer of white kaolin primer, from locally available sources, mixed with animal glue was applied. This formed the surface on which the painting was executed.

Preparatory Drawings. It could not be clearly established if the preparatory drawings were made using rubbings from cartoons. However, it does seem that the drawings may have been done directly on the wall after laying a grid with a snap cord. Although there is no clear indication of this process for transferring a drawing to the wall surface, this technique becomes apparent with observation of the levels of the various features of the wall painting. For example, the pedestal base of all the figures is on the same level, as is the *urna* (mark on the forehead of Buddha).

Painting. After the preparatory drawings were executed on the wall, they were filled in with light colors similar to those seen in the incomplete paintings on the walls flanking the Maitreya statue. Gold leaf was used to fill in areas representing flesh. Also, gold powder mixed with animal glue was used to paint ornaments. The resulting effect is uplifting. As light falls on the different figures in the wall paintings at different times of the day, the figures seem to come to life.

To better understand the materials and technique used in the Chamba Lakhang wall paintings, systematic scientific analysis will be required. Some literature is available on the subject, but more information is required to fully appreciate and understand these paintings from a technical standpoint.

Condition Assessment of the Chamba Lakhang Wall Paintings

Before devising the documentation strategy for the wall paintings in the Chamba Lakhang, it was necessary to develop a uniform standard for recording the condition of the paintings within the broader parameters of the problems of deterioration in the wall paintings of the Ladakh region. To achieve this, we carefully conducted a brief survey of paintings of different representative periods and sites in the region to develop a standard condition assessment legend.

Another important consideration was that trained conservators would not always be available in the future for documentation on other conservation sites. Therefore, we trained para-conservators (locals with some art or science background hired for short durations) specifically for the purpose of documentation.[5] For this group, it was imperative to keep definitions simple for recording the condition of the wall paintings without compromising the quality of the documentation. Therefore, distinctions were made on the basis of existing condition (as visible), not on the cause of deterioration, which would be assessed separately by the lead conservator and added to the report, along with results from scientific examination of materials and technique, and so on. In this way we formulated the condition assessment methodology.

In order to have access to all painted areas, we acquired a trolley of the cuploc type (a multipurpose scaffold system that allows easy assembly in tight spaces). This was important because pillars obstructed the movement of the trolley, and it had to be disassembled and then reassembled around the obstruction several times.

Before we started the condition assessment, detailed photographic documentation was carried out to record the condition of the wall paintings and various problems. Since the village of Basgo does not have electricity during the day, the interior of the temple was illuminated with solar lanterns (portable lighting devices that use a photovoltaic panel to convert sunlight to electricity and charge the battery). A small generator was also employed for additional illumination and for photography.

An initial survey of the wall paintings was conducted to identify typical problems. The parameters defining the paintings' condition were also established. For two days, the assessment team familiarized itself with individual problems and their identification before beginning the documentation.

For purposes of graphic documentation, the walls were divided into arbitrary panels according to their composition, with care taken to avoid overlaps and dividing the figures. These panels were then measured and named. The important points in a figure were measured relative to the ceiling, as the floor was uneven, and plotted on a graph. Subsequently, line drawings were prepared. The condition of the wall paintings was recorded by laying transparent sheets over the line drawings and noting the relative position of the problems on them. The condition assessment criteria and format were adapted from the Getty Conservation Institute's project for the conservation of the tomb of Nefertari in Egypt. I have used the methodology developed for this project for my work in Ladakh and other places (see Cather 1991; Corzo and Afshar 1993).

After a detailed survey of the deterioration problems in the Chamba Lakhang, the condition of the painting was broadly categorized as follows:

- *Delamination.* This refers to separation of various layers within the composite structure of the wall surface. Two main types of delamination were recognized: (a) coarse plaster separation from wall (separation between the wall surface and coarse plaster) and (b) fine plaster separation from coarse plaster (separation of paint layer with primer from coarse plaster, as well as separation within the coarse plaster itself).
- *Cracks.* The cracks were divided according to their position and nature. A textile micrometer was used to broadly differentiate between minor cracks and fine cracks. Four main crack types were identified: (1) structural cracks (cracks caused by structural changes and extending down to the wall); (2) major cracks (cracks extending through the coarse plaster); (3) minor cracks (cracks extending through the primer and whose width measured not more than 1.5 mm at the widest point); and (4) fine cracks (cracks extending through the surface coating and/or paint layer and whose width measured less than 0.5 mm).
- *Losses/alterations.* To define the various types and the nature of loss and alteration, the visible layer was used as a reference point. The main cause of discoloration is water seepage, so any change in the hue of the original color differentiated from the rest was recognized as discoloration regardless of the specific cause and nature; for example, discoloration due to oxidation of pigments was not separately marked. Five main types of losses were identified: (1) wall visible (implying loss of ground and subsequent layers); (2) coarse plaster visible (implying loss of the top surface of ground and subsequent layers); (3) fine plaster visible (implying loss of primer and paint layer); (4) primer visible (implying loss of paint layer and/or protective coating); and (5) flaking (implying potential areas of paint loss).
- *Surface deposits/previous interventions.* This broad category describes any obscuration of the paint surface. It does not distinguish between that caused by a prior intervention and that caused by a foreign substance, for example, between repainting and soot. Seven types of surface obliteration were identified: (1) soot (deposits from burning incense and butter oil); (2) grime (deposits from sweat and oil due to human contact with paintings); (3) clay (clay and/or kaolin from the primer washed down from the upper portions of the wall painting and deposited on the paint surface in the lower parts); (4) dust and dirt (although a uniform coat of dust and dirt is present, only those areas where it completely obliterates the paint layer were noted); (5) repainting; (6) clay infills; and (7) cement infills.

Emergency Treatment of the Chamba Lakhang Wall Paintings

During my first visit to the site, I observed that plaster along the major structural cracks in the painted walls had fragmented due to mechanical stress, with fine cracks radiating into the adjoining plaster. Water seepage had removed the underlying plaster in some areas around these cracks, so that the paint layer and parts of the plaster were hanging precariously. Some of these undermined fragments had already fallen. Slightly larger pieces of plaster that survived the fall had been picked up by the caretaker for safekeeping.

We decided to take emergency measures to protect the paintings for a number of reasons. It was obvious that by the time funds could be raised for conservation and restoration, additional losses would have occurred. In addition, there was road-widening activity in the vicinity, and tremors from blasting could increase the loss. Further, the temple monks use a yak-tail mop tied to a long stick for removing cobwebs and dust from the walls, and in some places this has resulted in damage to the paint layer. The monks have been asked to discontinue the practice, but sometimes devotees decide to clean the temple themselves and wipe away the flaking paint layer (it is not possible to monitor visitors and devotees at all times).

It was determined that future damage and loss would occur primarily around the areas adjoining the structural and major cracks, in particular, from important areas. For example, in one panel on the west side, the entire face of the Dhyani Buddha is lost. However, one small fragment on the upper edge of this loss defines the topmost position of the hair knot, thus giving a reference for the dimension of the face. The plaster adjoining the cracks, in particular, in areas that also had been affected by water seepage, was delaminated from the wall in most areas, posing a serious threat to its survival. Therefore, as part of the documentation and condition assessment of the wall paintings in the Chamba Lakhang, it was decided to seek additional funds to undertake emergency treatment.

Emergency treatment was designed with the following considerations:

- Intervention should be unobtrusive so that visitors and locals would not look at the treatment as defacing the images.
- Treatments should last without monitoring for a long period and without causing further damage or deterioration.
- Emergency intervention should not be taken as one of the processes of the actual later conservation.
- Integrity of the paint layer should be maintained by not introducing any material for consolidation or waterproofing, so as to allow the conservator a wider choice of techniques and materials at the time of the subsequent restoration.[6]
- Adhesive used for securing damaged areas should be reversible after a long period without affecting the paint layer.
- Adhesive should be soluble in a range of solvents to allow for maximum leeway in handling the paint layer later.
- Emergency intervention should be economical to carry out.
- Emergency intervention should be repeatable under a wide range of conditions typical to the region of Ladakh.
- Emergency treatment should be easy to carry out to allow for the possibility of using para-conservators.

Treatment Approach

Keeping in mind the above considerations, we fully explored the possibilities for securing the damaged areas. The chosen treatment was to secure the plaster pieces with synthetic fabric strips and also to consolidate major areas where the paint was flaking.

After testing different adhesives and facing materials, we decided against covering the entire damaged area with either long-fiber tissue paper or cloth, which would lead to problems during the intervening time and also during removal. It was also observed during tests that application of Paraloid® B72 for fixing the colors to allow for the use of a water-based adhesive, such as bone glue, substantially changed the tonal quality of the paint layer. The paint surface in many areas has a deliberate matte finish that would be affected by saturating it with a fixative. Thus any water-based adhesive and use of a fixative such as Paraloid® B72 had to be excluded.

After detailed tests, it was decided to secure the plaster and paint layer with strips of a fine-mesh synthetic cloth (monofilament stain-resistant polyester, 70 mesh) used for screen-printing. The mesh is resistant to chemicals and can be stretched across the cracks with ease, thus reducing slack. The fabric is nonhygroscopic, with a low thermal coefficient of expansion. This is important in the extreme climatic conditions of Ladakh. The use of a synthetic fabric was also dictated by the fact that it was primarily pieces of plaster that had to be secured in place, and paper or similar commonly used materials would not have been able to hold the weight of the plaster pieces if they were to fully detach.

Pidicryl® 126 was selected as the adhesive for securing the mesh strips to the damaged areas because it has properties similar to those of Plextol® B500 (methyl methacrylate/ethyl methacrylate copolymer),[7] which has been extensively tested for such properties as reversibility and has been in use for a long time. The main feature of interest was that Pidicryl® 126 can be thickened with toluene to form a paste that does not percolate into the paint layer but forms a film on the surface when applied, which can be easily removed without causing any visible changes. Pidicryl® 126 thickened with toluene (7% by volume) was tested for reversibility, penetration into the paint layer, alterations to the pigment, ease of application, strength, and load-bearing capacity in an area of plain plaster with damage similar to that on the painted area and also on mud bricks similar to those used in the walls.

Pidicryl® 126 also forms an emulsion with water that can be diluted to desired levels for greater penetration into the mud plaster. This emulsion, diluted to form a solution (5–8% in water), was used to consolidate the areas where the paint layer/ground had become powdery and to fix flaking paint.

Added advantages of the Pidicryl® 126 adhesive are its low peel strength (i.e., less force would be needed to peel off the mesh fabric at the time of removal) and high shear strength (i.e., more force is needed to pull the adhesive away from the wall). If pieces of plaster dislodge for some reason, they will be held in place and not fall.

Tests were carried out to check the reversibility of the emergency treatment. Toluene, acetone, isopropyl alcohol, and trichloroethylene were found suitable for removing the adhesive from the paint layer. The best results for removing the mesh strips from the wall, however, were obtained with trichloroethylene (TCE).[8] This swelled the adhesive, allowing for the easy removal of the mesh fabric. Excess adhesive could be removed by light rubbing with the fingertips or by scraping with a scalpel without affecting the paint surface.

Treatment Application

The emergency treatment was carried out in 2000 as part of the condition assessment and documentation program. The mesh fabric was cut into strips approximately 1 centimeter wide to cover smaller fragments and approximately 2 centimeters wide for the larger fragments. The length of the strips was adjusted according to the size of the damaged area. One end of the strip was placed over the undamaged part of the paint layer on one side of the crack, and adhesive was applied over the fabric with a brush. This allowed a minimal quantity of adhesive to pass through the mesh cloth and onto the paint layer. After the adhesive dried, the mesh strip was extended to the opposite side of the crack, beyond the damaged area, and held slightly taut; then the other end was fixed likewise. The entire mesh strip was not pasted; selected points along its length were adhered to ensure that all the intermediate undermined plaster fragments were held to the mesh with the adhesive. If a fragment was small, about 2 to 4 square centimeters, it would need only one adhesion point; for larger fragments, about 6 square centimeters and greater, more adhesion points would be required. Thus a single strip would cover about three or more fragments in a straight line. It is as if the crack has been "stitched" with the mesh strips (fig. 2).

This approach, along with the elasticity of the mesh strip, would prevent separation and fresh breakage of the plaster if there were any movement along the crack. In an extreme situation, if a plaster fragment were dislodged, it would still be held by at least one point (fig. 3). The adhesive is strong enough to hold some weight, but it will give way if there is increased pressure, thus preventing new damage. Furthermore, with this approach, in the event of any major movement in the building or an accident, the paint layer is likely to be stripped off the ground (*strappo*) and can be reattached later in extreme circumstances, thus minimizing the loss.

Pulverized areas and flaked paint were consolidated along structural and other major cracks before the mesh strips were applied. Pulverized ground was consolidated with Pidicryl® 126 diluted in water (5–8%). Small fragments along the edges of the cracks and larger parts of plaster were also consolidated with the same solution. This solution was also applied to fix flaking areas. In this case, drops of the adhesive were placed near the damaged area with a brush or

FIGURE 2 Section of the Chamba Lakhang's northeast wall, with a deep structural crack running down the center. The crack has been "stitched" with mesh strips (white patches) along its length.

FIGURE 3 Portion of treated painting with schematic detail showing the location of mesh strips (yellow outline) used to secure plaster on either side of the cracks (blue). Arrows indicate adhesion points and the direction of forces that hold fragmented plaster in place.

a syringe, and the solution would then get absorbed by capillary action. The flaking paint was settled by applying minimal pressure with fingertips over silicone paper.

In order to improve the penetration of the adhesive solution, alcohol was used as a surfactant; an added advantage was that it prevented water stains from developing. Further, since the relative humidity is very low in Ladakh, drying is accelerated, which also proved advantageous because it allows for repeated applications if needed in a shorter time span.

Over time, the mesh strips applied during the emergency treatment darkened slightly due to the deposition of soot and dust, making them invisible when viewed from a distance.

Discussion

The Chamba Lakhang project is part of a larger effort to develop the methodology for documentation and condition assessments of a large number of sites with wall paintings in the Ladakh district. The aim is to provisionally conserve this art with minimal cost while simultaneously ensuring the quality and longevity of the sites through minor interventions. Several issues need to be addressed:

- It is important to have an ongoing dialogue with the community where the wall paintings are located and the stakeholders to ensure that the decision-making process is transparent and consensual. Vital issues relating to practice and ethics in conservation, especially in the context of infilling, need to be explained in detail and strategies adopted to educate the people. This will ensure the survival of the site until it can be conserved properly.
- It is important for the international conservation community to study and develop emergency treatment options, as this may be the last chance for the survival of a large number of monuments in India and elsewhere.
- There is a need to develop standard testing and examination procedures that do not depend on the use of costly laboratory facilities, since more often than not these are neither accessible nor affordable in India and elsewhere. Also helpful is the development of a shared database of materials used for conservation in the West and their possible substitutes in countries such as India where there is no specific marketplace for conservation materials. This can be achieved through the active collaboration of international institutions.

Postscript

Work on the restoration and conservation of the wall paintings in the Chamba Lakhang commenced on April 10, 2004, three and a half years after the documentation and emergency treatment were carried out. A ceremony for the removal of the spirits from the images was conducted prior to commencement of work. The first phase of the project was completed by October 2004, during which the plaster and paint layer and areas of delamination were consolidated.

The final phase, involving cleaning and reintegration, will be carried out in 2006. A review of the emergency treatment showed that no fresh damage had occurred. In several areas, plaster fragments had dislodged from their surroundings, but they were held in place by the mesh strips, as intended.

Acknowledgments

Gratitude is extended to the people of the village of Basgo and to the Basgo Welfare Committee, who have over the years spearheaded the movement to restore the site of the Basgo citadel to its original glory in a sensitive and educated manner, much against the prevailing trend to bring down and rebuild culturally important structures in the Ladakh region. Thanks are also due to Jigmed Namgyal and Tara Sharma of the Namgyal Institute for Research in Ladakhi Art and Culture (NIRLAC) for the institutional support provided to the conservation movement in Basgo and to Martand Singh, chair of the INTACH (U.K) Trust, for providing financial support for the condition assessment and emergency treatment of the wall paintings in the Chamba Lakhang.

Notes

1 NIRLAC is a local nongovernmental organization established by the former royal family of Ladakh, with the objective of preservation of cultural heritage in the region. It has a wide range of activities, including documentation, listing, training, and assistance to local museums and village communities for maintenance of their collections.

2 Lamaism is the Mahayana Buddhism of Tibet and Mongolia headed by the Dalai Lama.

3 Interestingly, both images are painted in gold color and are identified on the basis of the iconography.

4 In the *Vishnudharmottara-Purana,* the chapter titled "Chitrasutra" elaborates on the technique and materials for painting. It gives detailed formulations for the preparation of the wall surface before painting, preparation of various types of brushes, colors, etc. It also provides the artist with instructions for visualization of the subject matter, as well as iconographic and iconometric details.

5 Most conservation projects in India rely on the use of skilled craftsmen, especially for the postconservation phase. The practice has not yielded positive results in terms of training these craftsmen, particularly for conservation purposes, since there is no attempt to retain them for other projects. In view of this, I have trained a number of craftsmen and other individuals to handle basic conservation techniques for my projects, thus preparing a small number of conservation technicians who, for want of a better term, are referred to as *para-conservators.*

6 At the time of the documentation, there was a possibility that for reasons such as funding the actual conservation would be carried out by another team.

7 In India, polyvinyl alcohol emulsion and polyvinyl acetate (PVA) have been the adhesives of choice for the consolidation of wall paintings. The obvious shortcomings of these are fairly well understood, but they continue to be used in most conservation circles because many alternatives used in the West are not available in India. In 1997 I initiated a research project at the Indian National Trust for Art and Cultural Heritage to find suitable substitutes for some of these commonly used adhesives. One adhesive was Plextol®, for which the substitute identified was Pidicryl® 126, a methyl methacrylate–based adhesive having an identical molecular structure, except for the difference in the additives, which could not be identified.

8 Trichloroethylene (TCE) is a hazardous chemical that mainly affects the central nervous system, causing headache, nausea, dizziness, clumsiness, drowsiness, and other effects similar to those of being drunk. TCE can also damage the facial nerves, and it can cause skin rash. Heavy exposure can damage the liver and kidneys. TCE causes cancer in animals and may cause cancer in humans. To minimize these risks when using TCE on-site, I used a fume extractor system consisting of a hood placed close to the area of application and a blower that directs air to the outlet. Further, used swabs were disposed of in a closed container, and proper ventilation of the chamber was ensured at all times.

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Surveying Paradise: The Conservation Survey of a Yuan Dynasty Wall Painting on a Clay Base

Kathleen M. Garland

Abstract: *When the Nelson-Atkins Museum of Art was built in 1933, a central gallery was designed specifically to display the* Paradise of Tejaprabha Buddha and Attendants *(ca. 1300–1324), a Yuan dynasty wall painting on clay, 7.13 meters wide by 14.83 meters high. The architectural atmosphere of a traditional Chinese temple was created for the gallery by adding a wood and clay-based gilded lacquer fifteenth-century temple ceiling. The space is enclosed by a set of seventeenth-century clay-based lacquer and wood gate panels. This paper focuses on the conservation survey undertaken on the* Paradise of Tejaprabha Buddha *wall painting. It describes the equipment and processes used for the survey and discusses the findings.*

The draft protocols from the Graphic Documentation Systems in Mural Painting Conservation Seminar (GraDoc), held in Rome in 1999, were used to establish the following goals for the survey: (1) document the condition of the art to monitor changes; (2) determine the conservation needs; (3) produce high-quality photography of the art for publication and scholarly research; and (4) conduct scientific analyses to record the use of historical materials and techniques, both for scholarly research and to assess the condition of the art.

Ultraviolet lights, a binocular microscope, a metal detector, and a digital boroscope were used to perform the condition assessment. Historical refurbishments done in China and the restoration history prior to and during installation are described. More than forty samples were taken to analyze the original materials, the Chinese refurbishments, and the more modern restorations. The results of the survey were recorded using Adobe Photoshop 7.0, which made it possible to demonstrate graphically both the deterioration and the physical history of the painting.

The Nelson-Atkins Museum of Art in Kansas City, Missouri, has one of the finest collections of Chinese art in the United States. In 2001 the museum, with a generous grant from the Getty Grant Program, conducted a conservation survey of one of the museum's most important works, the wall painting *Paradise of Tejaprabha Buddha and Attendants,* ca. 1300–1324 (fig. 1). For the opening of the museum in 1933, this work, along with two others,[1] was installed in a room constructed to provide the ambience of a Chinese temple—the most popular gallery in the museum. This paper focuses on the conservation survey undertaken on the *Paradise of Tejaprabha Buddha* wall painting.

History of the *Paradise of Tejaprabha Buddha* Wall Painting

The *Paradise of Tejaprabha Buddha* wall painting comes from the main hall in the lower monastery of the Temple of Expansive Victory at the Guangsheng Monastery in southern Shanxi province, China. This temple is an important Buddhist center with ties to the Yuan dynasty imperial court. The significance of the wall painting is considerable, since few such large Yuan dynasty murals exist intact or in situ and in relatively well-preserved condition.

The wall painting, executed on clay and measuring 7.13 meters by 14.83 meters (w × h), depicts the Tejaprabha Buddha, whose name means "blazing light," surrounded by figures representing celestial bodies, including the sun, moon, and five planets of traditional Chinese astronomy. This painting was located on the wall of one of the gable ends of the hall; a similar painting on the opposite wall is now located at the Metropolitan Museum of Art in New York

FIGURE 1 Digital mosaic of the *Paradise of the Tejaprabha Buddha* wall painting.

City. Sometime before 1927, to pay for repairs to the building, the Guangsheng Monastery sold both wall paintings to the art dealer–scholar C. T. Loo, who was based in Paris (Anning Jing 1991). Other paintings believed to be from the same monastery can be seen at the University Museum, University of Pennsylvania, Philadelphia, and at the Cincinnati Art Museum, Ohio.

Removal and Reinstallation

The wall painting was removed from the temple sometime around 1930. Section lines where the painting was cut from the wall are still quite visible on the surface. It seems that the painting was pasted over with paper and possibly a peach gum (Anon. 2003),[2] then cut into small sections, roughly 40 square centimeters. These small sections were shipped to Paris and reassembled by C. T. Loo's restorers onto larger plaster of paris panels or blocks of varying sizes. The blocks were then shipped to Kansas City for installation in the Nelson-Atkins Museum of Art according to the recommendations from Rutherford Gettens and George Stout at the Fogg Museum at Harvard University, which seem to have been followed fairly closely (Nelson-Atkins Museum archives n.d.; Straus Center for Conservation n.d.; Stout and Gettens 1932).

The *Paradise of Tejaprabha Buddha* painting was installed on a wall at the museum in a specially designed gallery based on the architectural style of a traditional Chinese temple. This gallery was created using a wood and clay–based gilded lacquer fifteenth-century temple ceiling, acquired from the Zinhua Temple in Beijing, and then enclosing the space with a set of seventeenth-century clay-based lacquer and wood gate panels donated by Loo.

The plaster blocks carrying sections of the painting were attached to the brick wall of the gallery with metal wire twists in each corner of the blocks (fig. 2). Holes were made through the front surface of the painting for these twists. Angle iron was used to support each plaster block from the

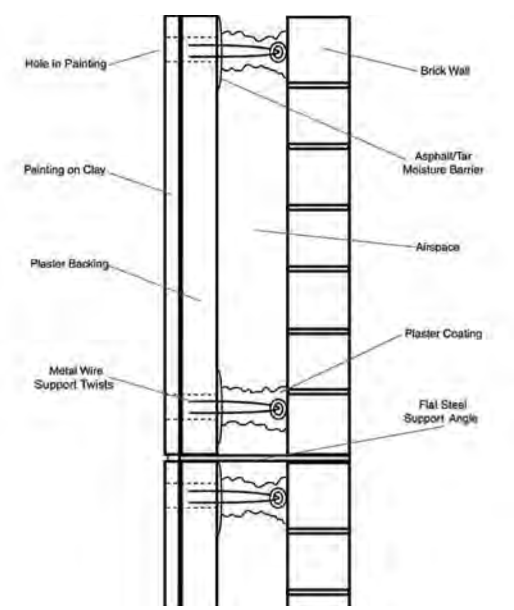

FIGURE 2 Schematic showing attachment of individual plaster blocks of the *Paradise of the Tejaprabha Buddha* wall painting.

bottom, and the wire twists were encased in plaster of paris at the back of the painting to make them rigid. A hard, unidentified filling material was used as a mortar in the 1-centimeter gap between all the plaster blocks. This mortar was given a wash of color to blend somewhat with the adjacent painting. When viewed from above, there is a gap of about 8 centimeters between the painting and the brick wall, but there is no direct access to the back of the painting. This prohibited any X-radiography. The left side of the painting may have been cut slightly to fit within the architectural space. No subsequent conservation intervention has been documented.

FIGURE 3 Physical setup for digital imaging of the wall painting.

Conservation Survey

The following goals for the conservation survey of the *Paradise of Tejaprabha Buddha* wall painting were established based on the draft protocols from the Graphic Documentation Systems in Mural Painting Conservation Seminar (Schmid 2000) held in Rome in 1999:

1. Document the condition of the art to monitor changes.
2. Determine the conservation needs.
3. Produce high-quality photography of the art for publication and scholarly research.
4. Conduct scientific analyses to record the use of historical materials and techniques, both for scholarly research and to assess the condition of the art.

The conservation survey was undertaken over a six-month period by two conservators from the Nelson-Atkins Museum and a contract graphic designer.[3]

Photography

In preparation for the condition assessment, the entire *Paradise of Tejaprabha Buddha* wall painting was photographed. The painting had not been sufficiently studied previously, in part because the gallery architecture and the size of the painting made photography very difficult. Consequently, no photographic record exists of any deterioration over time. However, new developments in digital photography now make publication-quality documentation possible (Miller, Meluso, and Garland 2003).

Two photographers, one from the museum's photo department and the other a contractor, worked more than two months using a Mamiya RZ67 camera with a 50 mm lens with an Imacon FlexFrame 4040 digital camera back. Images (95 MB) were captured on a Macintosh PowerBook G4. A special setup was fabricated for the camera and two Broncolor Pico strobe lights, which were installed on special dollies to allow precise movement horizontally and vertically (fig. 3). Laser levels were used to align the camera to take eighty images covering the entire painting. Each area photographed also had a corresponding raking light image, which uses oblique illumination to cast shadows that reveal topographic features of the surface. A contract digital technician then took ten days to "stitch" the eighty digital images together using Adobe Photoshop 7.0 to achieve a complete photograph of the painting (see fig. 1). These high-quality images can be used to monitor the painting's condition over time, and the images can be easily shared with scholars around the world.

Long-term preservation of digital material has become an increasing concern because of obsolescence. All our digital files are stored on DVDs or CDs. There are at least three copies: one is kept in a Powerfile C200 jukebox in the photo department. This allows for easy access to the images while reducing damage to the discs. A spare copy is also kept with it. A third copy is kept in a fireproof safe in our off-site art storage. A copy of any conservation-related documentation is kept in the conservation department.

Setup for the Condition Survey

An area adjacent to the wall painting was roped off so that visitors could observe the survey in progress. A notebook explaining various aspects of the survey proved very popular with visitors and staff. A scaffold tower was installed in the gallery for the conservators. Electric lifts and ladders were also available. The gallery was connected to the museum's computer network so that two laptops could be used by the team. Three mobile stations were set up, including a 30 GB computer with a slave drive, DVD-ROM, and large monitor on the ground station. Another station for a laptop was set up on the scaffolding.

Examination and Documentation

The *Paradise of Tejaprabha Buddha* wall painting was examined using a low-power binocular microscope to inspect the surface; a digital borescope to investigate behind the painting; and a metal detector to locate metal attachments. Ultraviolet illumination of the painting was helpful to distinguish overpaint. Archives at the Nelson-Atkins Museum and other institutions were also consulted for the history of the painting, including installation.

Documentation was done using Adobe Photoshop 7.0 on the images previously taken by the photo department. We chose to use this program because it is commonly available and unlikely to become obsolete in the near future, unlike most custom-made programs. Each of the eighty digital images, representing an area of about 127 square centimeters on the painting, was used to record information. The raking light image of each area was also included. Fifteen separate Photoshop layers were created and color coded to document different types of information: cracks, exposed ground layer, restoration, and so on (figs. 4–7). One layer was dedicated to written technical notes. The layers can be stitched into mosaics that can be studied individually or together, as in figure 7. The Photoshop zoom tool was especially useful, often allowing the conservator to conduct the examination of the painting on the screen, then check the painting on the scaffolding. The resulting electronic records are easy to store and search and can be used by scholars worldwide, unlike the paper or transparent plastic sheet documentation used in the past.

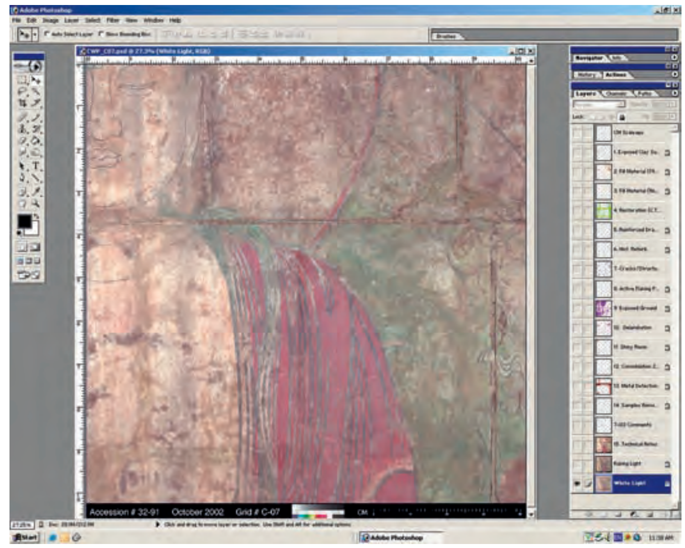

FIGURE 4 White-light survey layer as seen in Adobe Photoshop 7.0.

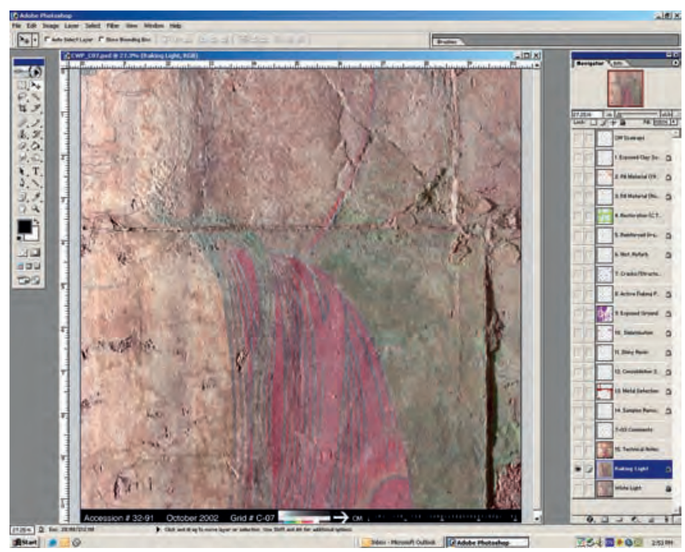

FIGURE 5 Raking light survey layer revealing topographic features of the wall painting.

Materials and Condition

John Twilley, an independent conservation scientist, analyzed some forty samples of the wall painting (Twilley 2003; Twilley and Garland 2003). Some of the findings from these analyses are described here.

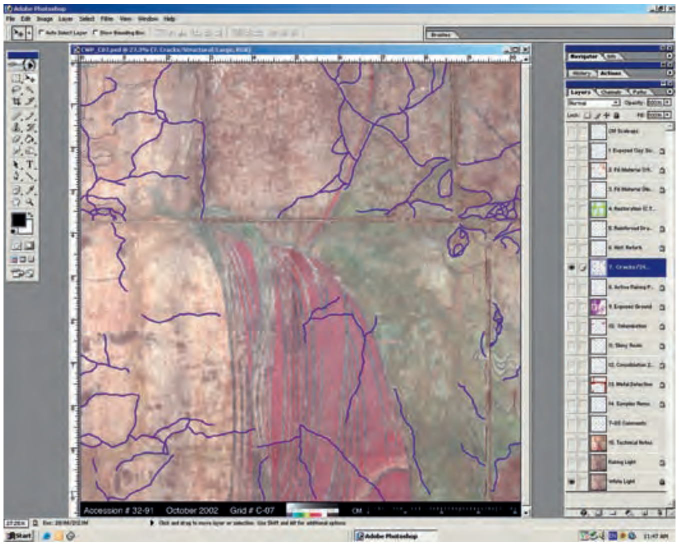

FIGURE 6 Survey layer revealing cracks.

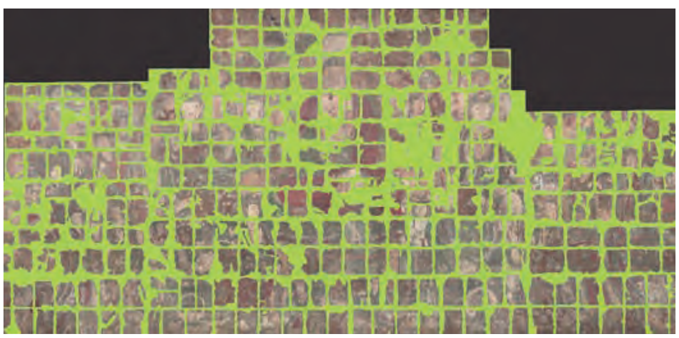

FIGURE 7 Assembled mosaic showing 1930s restoration.

Paint Layers and Pigments

The wall painting consists of a layer of tempera paint over a white ground, mostly kaolin. The paint medium could not be definitively identified, but it is likely to be water based. The original palette includes white kaolin clay, gypsum (white), lead white, azurite (blue), red lead, cinnabar (red), hematite (dark red), iron oxide (yellow), lamp black, charcoal, and atacamite (green). Dissolution and recrystallization have occurred in many of the original pigments, probably due to water ingress. Some pigments, such as the atacamite, red lead, lead white, and gypsum, have chemically interacted with the environment and possibly with each other, which may have affected their chromatic value.

One of the more interesting observations is the possibility that the green atacamite is actually man-made from corroded bronze, not from naturally occurring copper ores. Traces of tin oxide are visible as distinctive square prisms in scanning electron microscope images of samples from the painting. These tin oxide crystals are found only in the green pigments. Furthermore, the structure of the tin compounds did not show any cleavage or fracturing, as might be expected had they been present in minerals undergoing pulverization for pigments. Another interesting observation is the use of red lead, or minium, under the cinnabar, perhaps to enrich the colors or to extend the use of cinnabar.

Restorations

The 1930s restorations are generally found where the painting had been cut from the temple wall into small sections. These restorations can be seen in specular and raking light, as well as with ultraviolet radiation. The restorations are done in plaster of paris and tend to run over the cut lines by 3 to 6 centimeters (see fig. 7).

The colors used on these restorations, presumably applied by C. T. Loo's restorers, are quite easily distinguished from the original pigments. Brush spatters were added to blend the colors. Sometimes whole areas of one color adjacent to a cut line were overpainted. The pigments used by the restorers include viridian green, copper arsenate colors, green synthetic malachite, red lead with organic red lake, and white lead (Twilley 2003).

The survey indicated that about 10 to 15 percent of the painting has been overpainted, though most areas of exposed ground and clay have not been restored, giving the surface a pleasing aged appearance. No restoration was done where mortar fills the centimeter-thick gaps between the plaster blocks on which the painting sections had been reassembled. The mortar was only color washed to blend in, and the filled gaps are clearly visible.

Under magnification, the painted surface appears to have been "skinned" where the surface layer has been removed by overtreatment, probably by Loo's restorers. To compensate, many of the black lines have been "reinforced" with additional black paint, either during the Kansas City installation or by the earlier restorers. A coat of a clear shiny resin is also visible on all the black outlines on the feet, hands, and faces. The resin may have been added as a consolidant, but more likely it was used to saturate and enhance the black lines, since it is restricted to important body parts. The material could not be identified, but correspondence in the museum's archives suggests that the resin might be Vinylite A,[4] a poly(vinyl acetate) resin recommended by Rutherford Gettens as a consolidant (Nelson-Atkins Museum archives).

Structural Concerns

The *Paradise of Tejaprabha Buddha* wall painting retains only about 2 centimeters of the original clay backing, which is made from vegetable fibers and dried mud. The fragile nature of the unfired clay support and the paint layers was of considerable concern when the survey began. Also of concern was the 1930s mounting system for the painting: the large plaster blocks seemed insufficiently held by the wire twists at each corner and by the steel angle irons under each block. The hard mortar between the plaster blocks has fallen away in places, suggesting that vibration has occurred between the blocks. However, this vibration does not seem to have affected any original material.

Gentle tapping of the entire surface of the painting and examination of the crack patterns indicate that little damage has occurred to the original structure since installation. The paint, clay, and plaster layers are surprisingly well attached. The exceptions are the restored areas between the original cut sections of the painting and the circular areas where the original paint and clay ground have been cut to insert the wire twists. Most of these areas sound hollow when tapped, though they appear secure.

Conclusion

At the start of the survey, the museum's conservation department anticipated that the delicate material might need some emergency treatment. However, though very fragile, the painting is in good condition, and no treatment is required. Most important, there is now an excellent visual record should any damage occur in the future. The conservation team plans to examine the painting every two years using the digital records. If there is no change in four years, we will monitor less frequently.

Resources for the project included the following:

- two photographers for two months
- digital technician to "stitch" the image for ten days
- two conservators and a digital technician for six months
- consulting conservator for four days
- conservation scientist for ten days
- curatorial assistance for three weeks
- information technology backup for one week

Digital technology was critical for our project. For the first time a complete publication-quality image of the *Paradise of Tejaprabha Buddha* is available. The individual images of the painting provided a perfect opportunity to record the survey results in digital format. As others have noted, the use of digital records for surveys has both advantages and drawbacks (Schmid 2000). The equipment is expensive and challenging to use in nonmuseum settings. The software programs and equipment require a fairly steep learning curve. A full-time digital technician (our technician was not a photographer) familiar with Adobe Photoshop is an essential member of the conservation team. Additional information technology expertise was needed at times, and digital obsolescence is a serious concern. The layer setup for Photoshop makes printing a complete hard copy of the survey results very expensive and time-consuming.

The time required to conduct the survey was probably about the same whether done on paper or digitally. Nevertheless, the benefits of digital technology for this project far outweigh the disadvantages. The digital reports are extremely easy to share, copy, manipulate, and search, which is critical for our goals of long-term condition monitoring and scholarly research.

Acknowledgments

I wish to acknowledge financial assistance from the Getty Grant Program for supporting the survey and from the Kress Foundation for travel assistance. I also wish to acknowledge the assistance of Marc Wilson, Yang Xiaoneng, Lu Ling-en, and Jason Stueber, art historians; Joe Rogers, Steve Bonham, Elisabeth Batchelor, John Twilley, Jerry Podany, Zhang Zhiping, Eric Gordon, Dale Benson, Paul Benson, Christine Downie, and Cary Beattie Maguire, conservators and scientists; Lou Meluso, Jamison Miller, and Edward Robison, photographers; Tim Graves, Travis Morgan, and Kevin Dowd, information technology specialists; and Dinah Henderson, administrative assistant.

Notes

1 A fifteenth-century temple ceiling and seventeenth-century gate panels.

2 Polysaccharide exudates of *Prunus persica*. In 1955 Ru Anshi briefly described how peach gum was used in methods for detaching the Tang dynasty tomb paintings at Zhangjiawan, Xianyang, Shaanxi province, in 1952. Steps: cleaning the mud on the wall surface with water from top to bottom, drying the wall with coal fire, attaching fabrics to the painting with peach gums, detaching the painting with a thin-bladed knife from bottom to top, and sandwiching the painting with woodblocks for shipping (Anon. 2003 [trans. Ling-en Lu, assistant curator, Nelson-Atkins Museum of Art]).

3 A team of American and Chinese specialists were consultants on the project. They included Zhang Zhiping, director and senior engineer with the Conservation Center for Monuments and Sites, Beijing; Eric Gordon, paintings conservator, the Walters Art Gallery, Baltimore, Maryland; and Luo Zhewen, architectural expert on the Advisory Committee to the State Administration of Cultural Heritage, Beijing.

4 Vinylite is the former trademark name for poly(vinyl acetate) resins currently sold by Union Carbide under the trademarks AYAC, AYAB, AYAA, AYAF, and AYAT.

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Determining the Internal Condition of the Leshan Buddha Statue

Zhong Shihang and Huang Kezhong

Abstract: *For the purpose of conserving the Leshan Buddha statue, a thorough examination of the present condition of the stone core was carried out using several geophysical methods. This paper reports the main findings of our work regarding the cracks on the face of the Buddha and the thickness of the external shell.*

The Leshan Buddha (Maitreya) statue is located at the confluence of the Min, Dadu, and Qingyi Rivers in southern Sichuan province, near the city of Leshan. Measuring 62 meters in height, it is the largest stone Buddha statue in the world. It was carved out of a cliff face during the Tang dynasty (618–907 C.E.), starting in 713 and ending ninety years later. The whole statue, including the face, hands, legs, and feet, was covered originally by a shell consisting of a lime and clay mixture. The eyes, mouth, eyebrows, hands, feet, and robe folds are painted (fig. 1).

Conservation work was done on the Leshan Buddha several times in the past. The latest, large-scale work was carried out in the 1930s and 1950s with the then-available techniques. In order to undertake thorough conservation and to obtain complete information on the statue's current state of preservation, we examined the stone core underneath the external shell using geophysical techniques (Zhong Shihang 2002).

Investigation

Stereoscopic photographs of the statue were first taken so as to document the present condition. Next, contour line maps were created focusing on the statue's front, two sides, and top (fig. 2). These maps were also used to locate test points on the statue. Then geophysical techniques, including electrical resistivity, acoustic methods, and a neutron probe (Zhong Shihang 2002), were used for the following purposes:

- to determine the thickness of the external shell covering the stone core, so as to virtually reconstruct the form of the internal stone core;
- to detect deterioration points on the stone core;

FIGURE 1 The Leshan Buddha.

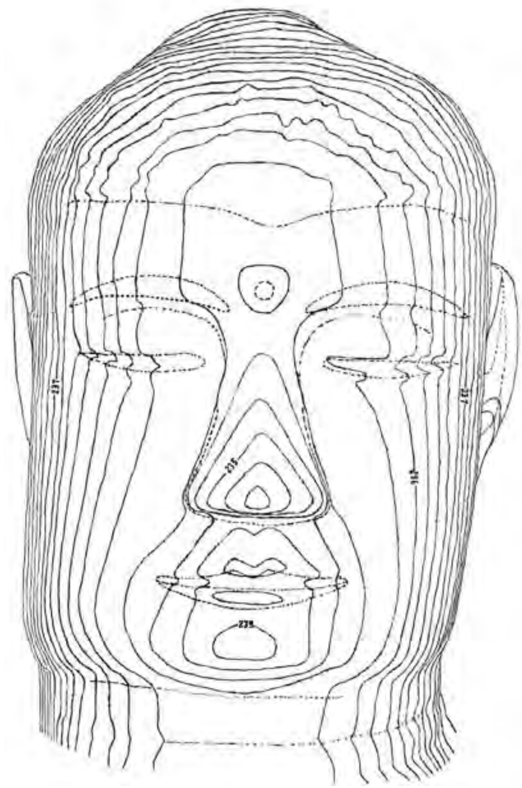

FIGURE 2 Stereoscopic map of the head of the Leshan Buddha.

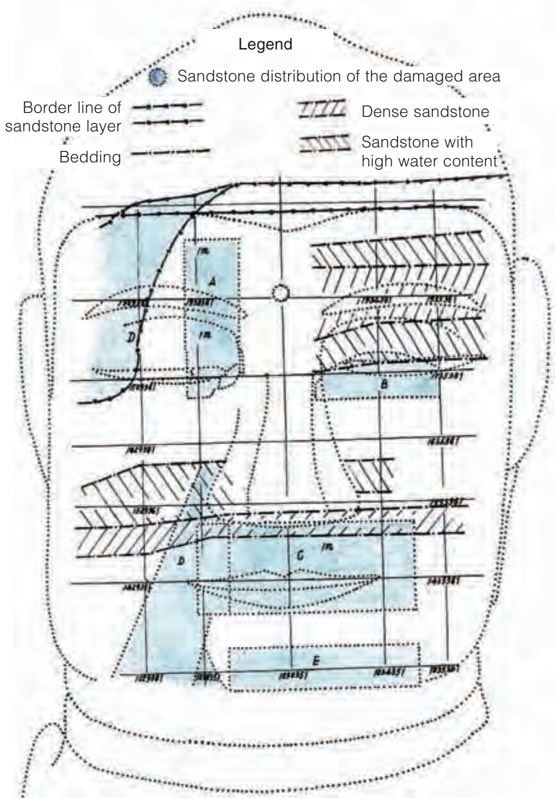

FIGURE 3 Distribution of the damaged areas.

- to detect cracks in the stone core, which resulted from the removal of the excess rock; and
- to locate the cracking points, from which seepage from the external shell occurs.

With this examination we also hoped to clarify the following questions and assumptions:

- Why does the Buddha seem to shed tears, have a running nose, and drip saliva for two to three days after moderate rain (10–25 mm/day)?
- Some scholars believe that the statue originally had a raised right arm that was later broken at the elbow and restored with other materials to the current position with the arm resting on the leg. This belief has been held for decades and still holds much currency today.[1]
- Some scholars believe that the statue's feet are not the original ones, which purportedly had been worn away and replaced with new ones made of other materials.

Results

The results are as follows:

1. The statue's forehead was carved from the cliff face, and it was then topped with lime mortar and a separately carved topknot. Electrical resistivity and sound wave instruments detected the joint between the forehead and the topknot. Rainwater is thus able to infiltrate the joint, enter the cracks in the head, and eventually seep out through the external shell.
2. Measurements of the thickness of the external shell were obtained: face, 10–50 centimeters; torso, 0–40 centimeters; hands, 20–40 centimeters; arms, 30–100 centimeters; feet, 60–120 centimeters. Measurements of the depth of weathering of the shoulder and torso that lack shell were also obtained; they range from 5 to 20 centimeters.
3. Deterioration points on the face were detected and their depths measured. The larger ones are located at the eyes, nose, mouth, and chin. A fractured triangular piece fell off at some point and became the major channel of the water coming from the top of the head (fig. 3).

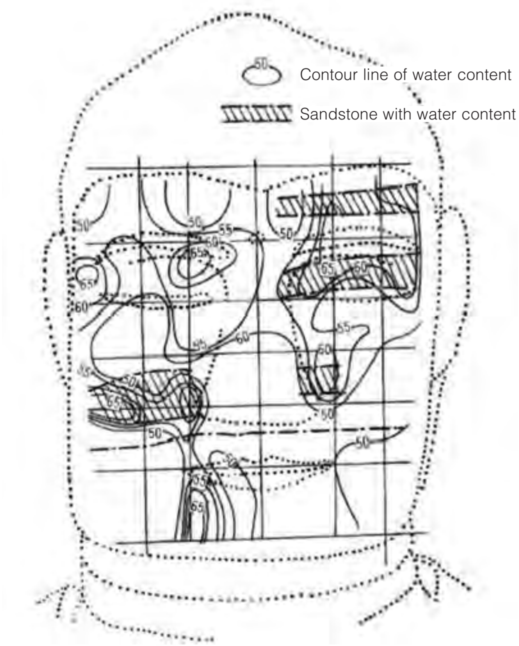

FIGURE 4 Moisture content map.

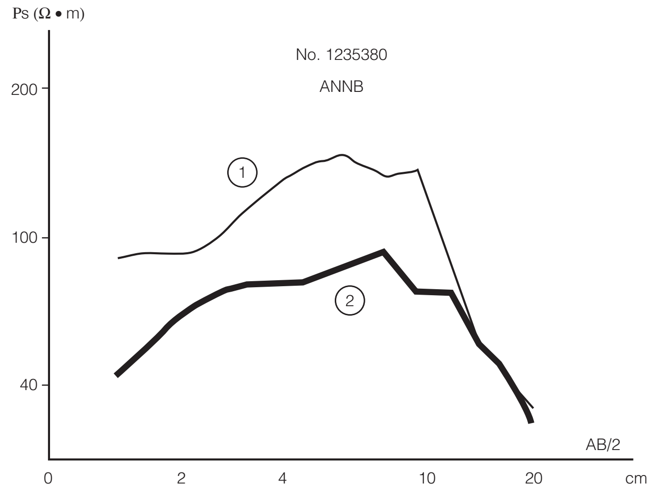

FIGURE 5 Contrast between two resistivity sounding curves (1) before rain and (2) after rain.

4. The right arm is intact. There is no evidence of fracture at the elbow. The current position of this arm is identical to the original one.
5. The feet are intact; only the right foot has suffered more damage from weathering.
6. The seepage areas were located (fig. 4). These were found near the eyes, the corners of the right eye, the right side of the nose, and the right side of the mouth, which correlate with the major damage on the face. Thus rainwater from the head seeps into the joint, drains from these damaged areas, and enters the external shell. This explains why the Buddha seems to cry even two or three days after rain.
7. A few large cracks that resulted from carving were discovered. The crack that cuts through the two knees poses the most danger to the statue.

Certain adjustments to procedures were necessary during examination with the geophysical instruments. The neutron probe sensor, which works by emitting neutron particles from a source, measures the moisture, but it could penetrate only to a depth of 7 centimeters. The thickness of the external shell of the facial part of the Buddha is 10 to 50 centimeters, and it is impossible for the instrument to locate the actual leaking points in the stone core. We circumvented this problem by using the probe after fifteen days without rain, thereby minimizing the possibility that rainwater had moistened the external shell. It was thus possible to locate accurately those areas with high moisture content, which presumably seeps out from the cracks in the stone core.

Another problem arose when measuring the thickness of the external shell with the electrical resistivity sensor. The instrument measures the different resistivities of the materials in the external shell and the stone core. Normally the material of the external shell has a low resistivity and the stone a high value. But if the shell contains certain other materials, its resistivity becomes high, and if the stone contains water, its resistivity becomes low. This dilemma was overcome by measuring the statue twice: after ten rainless days and after a moderate rain. Because rainwater soaked the shell and drastically changed its resistivity while the resistivity of the stone remained relatively stable, it was possible to detect the interface between the shell and the core by analyzing the different diagrams resulting from the two measurements (fig. 5).

Conclusion

Using geophysical techniques, we have been able to locate the stone core, cracks in the face, and seepage areas. We have also been able to measure the thickness of the external line and clay shell.

Notes

1 This item and the one that follows come from a roundtable discussion of the project group and the Leshan Giant Buddha research and conservation staff in 1990. Unpublished materials.

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