

PART NINE

Mogao Grottoes Cave 85 Project



Objectives of the Cave 85 Project

Neville Agnew and Li Zuixiong

In 1996, after the first phase of collaboration between the Dunhuang Academy and the Getty Conservation Institute, followed by independent review of the successes and shortcomings of the work undertaken beginning in 1989, it was jointly agreed to address the problems of deterioration of wall paintings at the Mogao Grottoes and their conservation by a systematic and methodological process. Cave 85 was chosen for this purpose, and it was further decided that an extensive phase of research and testing would precede any intervention. Moreover, among the objectives of the project were **training and dissemination of the results, particularly** in the northwestern regions of China where similar sites and conservation problems are widespread. At the same time a collaborative relationship was established between the State Administration of Cultural Heritage of China, the Getty Conservation Institute, and the Australian Heritage Commission for the development of national guidelines or principles for heritage sites in China. These principles, issued by China ICOMOS in 2000, base conservation decisions, processes, and implementation on a site's cultural values and significance. The China Principles were used as the guiding precepts in the cave 85 project.

The papers that follow cover many, but not all, of the results and outcomes of the project. First, they reflect the methodology of the China Principles by following a sequence of bibliographic research, development of a significance statement, condition documentation, investigation and analysis of original materials and techniques, study of causes of deterioration, environmental monitoring, and testing—all undertaken before treatment was decided on. Some of the steps were done sequentially, others in parallel where expedient to do so. Before treatment began, a panel of experts convened

by the State Administration of Cultural Heritage reviewed the proposal. Coauthored papers reflect the collaborative nature of the project.

It would be unwise to state that all is now understood about the many afflictions seen in cave 85, or indeed at Mogao itself. The original materials and techniques that were used to create the art are complex, and the deterioration has occurred over many centuries and at different rates. More needs to be known about the art, in greater depth. Progress has been substantial, however. The cave 85 project led to an understanding of many technical problems of wall paintings applied to earthen plaster; detachment or separation of the earthen support from the underlying conglomerate rock; the nearly ubiquitous salts; flaking and disruption of the paint layers by deliquescent salts; migration of these soluble salts from the rock body under the influence principally of water vapor; binding media research; and importantly, the development of compatible materials for treatment. In tandem, the direct impact of visitors on the cave's environment was evaluated, as was the intrusion of air from the outside when the doors were opened. This research in turn formed part of a much larger effort to determine the safe visitor capacity of the site.

Questions remain: What is the nature and origin of the organic colorants used in many areas as washes over mineral pigments, apparently to create a subtle effect? Why in some instances is there analytical evidence for carbohydrates as well as protein in the binding medium? What is the contribution of atmospheric moisture compared with that of humidity emanating through the rock body? Debate will lead eventually to comprehensive and irrefutable understanding of these questions, which also

suggest future research for the Conservation Institute of the Dunhuang Academy to undertake.

Arising from the cave 85 project has been a significant initiative—the master's degree course at Lanzhou University with specialization in wall painting conservation. A collaboration of the Dunhuang Academy with the Courtauld Institute of Art and the Getty Conservation Institute, the course has now graduated its first four students, all staff members of the **Dunhuang Academy**. **These professionals** will be the core of a new generation of conservators at

Mogao whose influence will spread far beyond the confines of the site.

Finally, archives of the data (analytical, environmental, testing, and treatment, photographs and reports) from the cave 85 project are being kept by both the Dunhuang Academy and the Getty Conservation Institute for future access by conservators, researchers, and educators. An extensive report on the project is planned for publication (limited hard copy, as well as an electronic version on the Getty's Web site) in 2010.

The Significance of Cave 85

Wang Jinyu

Abstract: *Understanding the significance of a site is key to its conservation, management, and use. Cave 85 at the Mogao Grottoes, which was completed in six years (862–67 C.E.), is known for its unique historic, artistic, and scientific values. It has seventeen large illustrations of sutras, fourteen of which are in the main chamber. These are mainly related to Buddhist doctrines and daily life in the late Tang period. Certain new styles of painting that are found for the first time in cave 85 show Tibetan, central Chinese, and Dunhuang influences. The paintings and their inscriptions provide information on architecture, transportation, customs, musical instruments, weaponry, tools, and pottery. They also pose useful research questions, such as about the techniques and materials used and their source.*

In 848 Zhang Yichao, from an important Dunhuang family, evicted the Tibetans and recovered territory in the Hexi area that had been occupied by Tibet for years.¹ Later, he asked his brother, Zhang Yitang, to lead a delegation to present a map of the Hexi area to the Tang emperor Xuanzong to demonstrate his willingness to return the area to China and thus support the unification of the country. The emperor rewarded the family for their loyalty and brave actions. In 851 he appointed Zhang Yichao prefect of the eleven states of the Hexi Corridor (Gansu province) and awarded him the title Commander General of the Return to Allegiance Army, stationed at Shazhou (present-day Dunhuang). This led to greater influence and power in the area, and the Silk Road between Gansu and northern Xinjiang (about 1,000 km) again flourished. The Zhang family continued to expand their influence by using their authority and financial resources to build caves at the Mogao Grottoes, including caves 9, 12, 85,

94, and 138, which commemorate the family's meritorious deeds (Ma De 1996).

According to the Hong Bian Stele, dated to the Tang dynasty and located on the west wall of cave 17, Zhang Yichao's action was supported by a Tibetan high monk-official, Hong Bian. After the eviction of the Tibetan regime, Hong Bian was asked by Zhang to send one of his disciples, Wuzhen, with the delegation to the Tang emperor. The emperor favored Hong's loyalty and filial piety and granted him honorific titles (Li Yongning 1981). Therefore, Buddhism, which was already deeply rooted at Dunhuang, prospered with the support of Zhang's family and the imperial order from the emperor. Nearly one hundred caves were restored and constructed during the period of sixty-six years in the late Tang. During Zhang Huaishen's regime, the Dunhuang area was stable and prosperous, with a strong military that made possible the construction of large caves. Zhang Huaishen was also the first high-ranking official to construct caves to demonstrate his wealth, political authority, and social status and that of his family.

Historical Significance

Cave 85 was constructed between 862 and 867 (He Shizhe 1980), an unusually short time. The highest regional monk-official, Zhai Farong, built the cave to demonstrate his political achievements and family wealth, a practice common among many monks and secular officials of the time. Zhai died in 869, about three years after the cave was completed. The cave, known as the Zhai Family Temple, was managed by Zhai's family (Bibliothèque nationale 1994; Wu Mangong 1959).

Cave 85 contains a wealth of art, as well as information on religious practices and daily life. The main chamber alone houses fourteen illustrated sutra paintings, one of the richest collections at the Mogao Grottoes. However, the antechamber has been damaged, making it impossible to determine the original layout.

The wall paintings at Mogao have some non-Buddhist depictions. First, the portraits of donors were prominent and reflect the influence of the region's rich and powerful leaders, especially the Zhang family, which had both political and religious influence. They controlled temples, contributed to the construction of family caves, such as Zhai Farong's, and painted portraits of family members as donors on the walls of cave corridors and at the lower portion of the east, south, and north walls (fig. 1). The portraits of main donors were life-size, and donors included grandparents and grandsons, uncles and nephews, in-laws, and servants painted in sequence. Toward the end of the Tang dynasty, the titles, rank of nobility, and official position of donors were described in great detail in the inscriptions. Thus these portraits were used for secular purposes. Cave 85 is one of the early caves showing this practice.

Portraits of the original donors remaining on the north wall of the cave 85 corridor include remnant inscriptions indicating Farong, his brother Chengqing, and Chengqing's sons, Huaiguan and Huairen (Ma De 1989). The portraits and inscriptions are consistent with the information from the Zhai family stele. Based on Library Cave Manuscript P.3720,



FIGURE 1 Portrait of Zhai Farong, monk-official and donor, on the north wall of the corridor.

the Zhai family stele was erected in front of cave 85. The stele was lost, but a copy of its inscription was preserved in the Library Cave.

Cave 85 is a typical family cave whose owners and donors were different at different periods. Portraits of Zhang Yichao, Zhang Huaishen, and, later, Cao Yijin and his son were painted on the corridor walls. Zhang Yichao and Zhang Huaishen were the regional highest administrative officials during the period of cave construction, and Cao Yijin and his son were the highest administrative regional officials during the period of cave restoration. During the regime of the Return to Allegiance Army, the highest regional administrative official was the main donor of his own cave but served also as honorary principal donor for caves constructed by others during and after his term. Therefore, the large caves constructed or restored at that period always had two portraits of the highest officials, current and former ones. Cave 85 was the first such cave.

Cave 85 was restored once during the Five Dynasties (907–60), and the portraits of donors on the south wall of the corridor and at the north side of the east wall in the main chamber were painted during its restoration. Cao Yijin was the leader of the Return to Allegiance Army at Guazhou and Shazhou, and his portrait and that of his son were painted on the south wall of the corridor. Based on the inscription, the fifth portrait at the north side of the east wall depicts Cao's eldest daughter. Her portrait also appears in cave 98, and the inscription indicates she married into Zhai's family and died before cave 98 was completed. Cave 85 was restored before the Tang dynasty emperor Tongguan's reign (923–25), and the people who restored cave 85 were grandchildren of Huaiguan and Huairen.

Artistic Value

Zhang Yichao evicted the Tibetans and recovered the Hexi area, thereby maintaining the integrity of Tang territory and reestablishing communication between western and central China. This historical incident and geographic setting helped to create the unique grotto paintings at Mogao, which display a combination of influences from central China, Tibet, and Dunhuang. These influences are reflected in the wall painting in cave 85.

The grotto arts at Mogao, as developed between 848 and 906 C.E. during the sixty-six-year Return to Allegiance Army regime, were based on High Tang and Middle Tang (Tibetan) art. Wall paintings in caves 9, 12, 14, 17, 85, 156, and

196 were outstanding and had not been seen before. Wall paintings illustrating the Redemption from Indebtedness and Lankavatara Sutras in cave 85 were among the masterpieces of late Tang arts and reflect also a Tibetan-influenced local style that had been popular for about two hundred years (Shi Weixiang 1985). Thus, as a representative of late Tang paintings at the Mogao Grottoes, cave 85 has very high artistic value.

Artistic Content

Cave architecture, wall paintings, and statues constitute a comprehensive style of grotto arts. By far the majority of wall paintings relate to Buddhism. Using paintings to relate a Buddhist parable is called narrative illustration,² and cave 85 has seventeen such large-scale paintings. Although this type of painting can be seen in other caves at Mogao, the paintings in cave 85 are done in great detail in the new style of the late Tang. A combination of lions and lotus flowers pattern was painted on the coffer (central ceiling panel) in the main chamber. Three layers of unusual decorative patterns surround the coffer, and valance patterns were painted around these. There are fourteen narrative illustrations of sutras on the four ceiling slopes and four walls of the main chamber. Depictions of the Lankavatara, Lotus, Maitreya, and Avatamsaka Sutras were painted on the east, south, west, and north slopes, respectively (fig. 2). The self-sacrifice story from

the Suvarna-prabhasa Sutra was painted on the east wall above the doorway. The other stories from the Suvarna-prabhasa and Vimalakirti-nirdesa Sutras were painted at the north and south sides of the doorway on the east wall, respectively. The stories of the *Bao'en Jing* (Redemption from Indebtedness), Amitabha, and Diamond Sutras were painted from the east side to the west side of the south wall, respectively. The stories from the Vishechachinta Brahma, Bhaishajyaguru (Medicine Buddha), and Ghanavyuha Pariprichcha Sutras were painted from the east side to the west side of the north wall, respectively. A depiction of Raudraksa battling with Sariputra is painted on the west wall. The sutra of the Wise and Foolish was depicted frame by frame on the lower south, west, and north walls. A partial depiction from the Yuan dynasty of the Manjusri and Samantabhadra Sutras paintings remain at the north and south sides of the west wall in the antechamber, respectively. The ceiling of the corridor has the thousand buddha motif from the Bhadrakalpika Sutra, and both the south and north slopes are adorned with fourteen auspicious symbols. Twenty-six figures, including late Tang monks, male and female donors, and servants, were painted on the south and north walls of the corridor and at the lower part of the east wall in the main chamber. Heavenly kings were painted on the east side of the platform. Paintings of stories representing different sects of Buddhism are scattered around the cave. The complicated compositions and rigorous execution of the paintings offer a splendid visual effect.



FIGURE 2 Ceiling painting pattern and paintings on the east, west, and south slopes (the south slope is the illustration painting of the Saddharmapundarika Sutra).

Unique Characteristics

The main chamber has fourteen narrative illustrations from a number of sutras. For example, the source of the painting of Raudraksa's Battle with Sariputra, which occupies the entire west wall of cave 85, was seventy-three volumes of sutras. Actually, this painting had already appeared during the Northern Zhou and Sui dynasties but did not reappear until the High Tang and the Tibetan regime. The eviction of the Tibetans by Zhang Yichao in 848 C.E. ended seventy years of subjugation for the people of the Hexi area. Using an entire wall to paint the sutra story of Raudraksa's Battle with Sariputra was a way to express the thoughts, feelings, and ideology of this formerly oppressed people through religious painting. The "righteousness overcomes evil" theme reflects their victory and their happiness about the return of Tang territory. People also used the sutra story of Redemption from Indebtedness to express their loyalty to the Tang

emperor. Consistent with Buddhist custom, the painting is located at the east side of the south wall, the right side being the supreme position. Although the narrative illustration still followed the tone of the middle Tang (Tibet), it revealed a strong national consciousness. For instance, the Tibetan princess Zhanpu was a leader of princesses from all nations in the narrative illustration of the Vimalakirti-nirdesa Sutra, which was painted during the middle Tang, but later the Tibetan princess was eliminated from the painting, as were Tibetan costumes.

In addition, cave 85 has more narrative illustrations from rarely depicted sutras, such as the Diamond, Suvarna-prabhasa, Lankavatara, Vishechachinta Brahma Pariprichcha and Ghanavyuha Sutras, than any other cave at Mogao. For instance, the depiction of the Prince Kalyanamitra *jataka* story, from the Redemption from Indebtedness Sutra, on the middle of the east part of the south wall consists of seventeen scenes, and the *jataka* story of the golden hair lion from the same sutra on the upper east part of the south wall has seven scenes (Li Yongning 1982). In addition, cave 85 has the largest number of inscriptions from the illustrated Lankavatara Sutra. A unique one is the pictorial representation of the sutra of the Wise and Foolish, which was illustrated scene by scene at the lower part of the south, west, and north walls in the main chamber. Among them, about twenty new stories are mentioned; a few, such

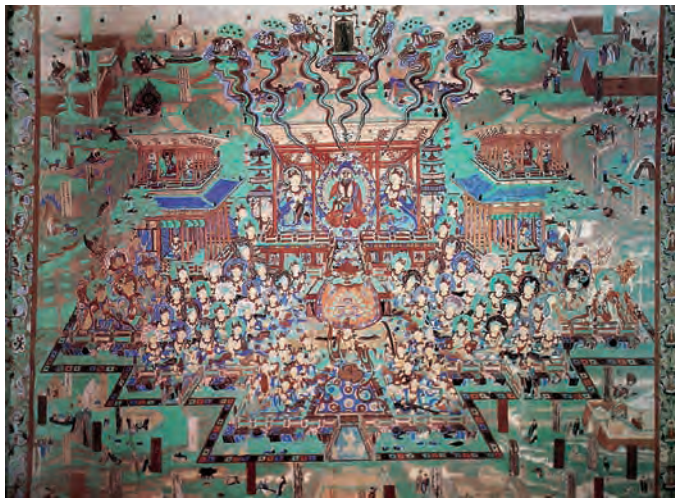


FIGURE 3 Painting of the Redemption from Indebtedness Sutra on the east side of the south wall.

as the sea god testing the boatman, the story of Gangata presenting seven treasures to the Buddha, the story of the Vajra-devas, and that of Sandanika appear for the first time in the wall paintings at the Mogao Grottoes.

Secular Influences

Portraits of donors are among the examples of the strong secular influences. In addition, daily living, common customs, and life stories were depicted; for example, the horse stable in a courtyard and fighting on both sides of a river from the parable of the children in the burning house in the Lotus Sutra (see fig. 2) on the south slope.

Other examples of secular influence in the narrative illustrations are Raudraksa battling with Sariputra, from the story of the Buddha overcoming demons, and Prince Kalyanamitra playing a musical instrument under trees (figs. 3, 4), from the Redemption from Indebtedness Sutra. The wedding scenes in the illustration of the Maitreya Sutra, including guests being hosted in a reed pavilion, the bride and bridegroom kneeling for the ritual, and the carrying of torches, are not only interesting but also depicted for the first time in cave 85 (Li Yongning and Cai Weitang 1990). Pictorial representation of the Lankavatara Sutra relied on scenes from daily life such as farming, eight people carrying a sedan chair, butchers, hunters, pottery making, weighing pork, looking into a mirror, and an acrobatic performance (fig. 5).



FIGURE 4 Section of the painting of the Redemption from Indebtedness Sutra, *jataka* story of the prince Kalyanamitra, playing a musical instrument (*zheng*) under the trees.



FIGURE 5 Painting of the Lankavatara Sutra on the east slope.

The use of framed narrative illustrations started in the high Tang. In the middle Tang these framed illustrations were used to elaborate the sutra story depicted on the ceiling panel. By the late Tang, the subject of these pictorial representations was no longer related to the painting shown above them. In cave 85, fifteen of these framed paintings from the sutra of the Wise and Foolish, located at the lower part of the south and north walls, are not related to other paintings. In the middle and late Tang, these framed paintings were used by monks as a visual aid in teaching and to help believers understand the doctrines. Compared to the framed narrative paintings, the narrative illustrations on the ceiling slopes depict the Buddha, disciples, bodhisattvas, and angels and are in a strict and sequential arrangement; framed didactic illustrations are less strictly ordered than are formal sutra narratives. The contrast between the two types of paintings is marked. For instance, the framed depiction of the Wise and Foolish Sutra has more secular than religious figures, and both costumes and scenes reflect the daily life of the Shazhou region at the time. Thus these illustrations also provide information on the local social life and were easier for people to enjoy, being dramatic and entertaining. This type of painting also gave artists more freedom and space to paint in a new way.

Diverse Styles

The composition and styles of the illustrated sutra story paintings in cave 85 essentially followed earlier patterns, but their overall layout, figure selection, story content, and scenarios represented a new breakthrough. For instance, the narrative illustration of the Redemption from Indebtedness Sutra is one of the highest in artistic value at Mogao. At the center of the painting are the Buddha and holy people; above

the Buddha and the colored cloud is an inscription of the story. The lower central part is a preaching scene, which is a preamble to the story. All the major stories of each chapter are located at the lower part and four corners. The painting uses several perspective approaches. All people and activities in the painting can be seen clearly. Each corner has its own story, but all stories are closely related, with detailed elaboration.

The wall paintings in cave 85 have other unique aspects, such as the arrangement of scenes and the design of figures. The illustration of Raudraksa battling Sariputra is one of the most unusual; unfortunately, most of the painting has been lost. The composition of the Redemption from Indebtedness Sutra is special; its figures are vivid, with two lovers sitting and talking face-to-face under trees and playing a musical instrument. All secular people in the illustration of the Lankavatara Sutra are full of energy. For instance, the butchery scene (fig. 6) shows the active life of ancient times.

In summary, the wall painting art in cave 85 was developed based on previous achievements, but it lost some degree of the sincerity and heavenliness of earlier Buddhist art. However, there were many innovative approaches showing daily life of people. The wall paintings in cave 85 are truly masterpieces.

Scientific Value

The wall paintings in cave 85 provide information on the history and development of science and technology in the late ninth century. In addition, many of the inscriptions, entirely



FIGURE 6 Scene of a slaughterhouse from the painting of the Lankavatara Sutra.



FIGURE 7 Painting of the Vishechachinta Brahma Pariprichcha Sutra on the east side of the north wall.

faded, can now be read using modern scientific examination techniques. The cave is, moreover, a good case study for Tang dynasty wall painting techniques and pigment sources. Pigment color change and the plant dyes and binding media used and their aging are important research subjects today.

Conclusion

Cave 85 has preserved seventeen large-scale narrative illustrations and other paintings. The depictions consist of doctrines, laws, articles, and the history of Buddhism, as well as sutra stories. The motifs also include figures of deities, illustrated sutra stories, architecture, auspicious symbols, animals, decorative patterns, and donors (in about eight categories). They provide insight into the life of ordinary people and feudal society's history, culture, politics, economy, science and technology, military, religion, architecture, transportation, costume, music and dance, and folklore. They are not only representative of Tang dynasty painting and polychrome statuary, but they also constitute a pictorial history of the Tang dynasty (figs. 7, 8).

Acknowledgments

The author expresses his gratitude to Peng Jinzhang, former director of the Archaeology Research Institute, Dunhuang



FIGURE 8 Painting of the Bhaishajyaguru Sutra on the north wall.

Academy, for his kind review of the Chinese content of this paper; and Po-Ming Lin for the translation.

Notes

- 1 Sanskrit terms in this paper come from W. Soothill and L. Hodous, eds., *A Dictionary of Chinese Buddhist Terms* (Chippenham, U.K.: Antony Rowe, 1937).
- 2 *Jingbian* in Chinese. This term has been translated as “sutra transformations” and “tableaux” by other scholars. See Murray 1994.

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Conservation History and Condition Survey of Cave 85

Xu Shuqing, Wang Xiaowei, Sun Hongcai, Li Weitang, Francesca Piqué, Lorinda Wong, Leslie Rainer, and Zheng Jun

Abstract: Cave 85, containing more than 300 square meters of painted surface, was excavated and decorated in the late Tang dynasty. The Dunhuang Academy began work in this cave in the 1950s, filling large plaster losses at the base of the walls and at the rear of the cave. Flaking and disruption of the wall paintings were treated in the 1970s with a mixture of polyvinyl alcohol (PVA) and polyvinyl acetate (PVAC) emulsions. At that time, areas of plaster detachment were also secured to the conglomerate with rock bolts. However, by the late 1980s and early 1990s, flaking and disruption had recurred on the west end of the cave, and new areas of plaster loss, through collapse, were visible. These phenomena were associated with periods of high humidity, due primarily to rain events at the site, in an otherwise dry climate and the presence of soluble salts. At the beginning of the Dunhuang Academy–Getty Conservation Institute collaborative project, the conservation history of the cave was reviewed and a condition assessment undertaken. A bilingual illustrated glossary that describes categories of deterioration was developed to ensure a common vocabulary for the project and for the site. The main deterioration problems recorded in cave 85 in 1998 included flaking, exfoliation, plaster disruption, and plaster detachment. The condition assessment showed that active deterioration is most pronounced and widespread over the entire west end of the cave. This, together with environmental monitoring and the analytical investigation to map salt distribution within the cave, was essential for the diagnosis of the causes of deterioration.

In the 1950s the Dunhuang Academy (then the Dunhuang Cultural Relics Research Institute), following a series of comprehensive surveys of the site, began a full-scale stabilization project at the Mogao Grottoes. Earth and straw

plaster repairs were used to fill losses of the wall paintings that had occurred over the centuries. In the 1970s the flaking paintings were treated with polyvinyl alcohol (PVA) and polyvinyl acetate (PVAC) emulsions, and areas where painted plaster had detached from the underlying rock conglomerate were anchored with steel rock bolts and cross-braces. But by the 1980s and early 1990s flaking and plaster separation problems had returned in a number of the caves, including cave 85. For this reason, cave 85 was selected by the Dunhuang Academy (DA) and the Getty Conservation Institute (GCI) as a project for the application of the China Principles methodology for the conservation and management of sites (formally, the *Principles for the Conservation of Heritage Sites in China*).

As described in the China Principles, the protection of historic and cultural sites should follow a methodological approach (see Piqué, Wong, and Su Bomin, this volume) that includes, as a preliminary step, the investigation and recording of both past and current conditions of the wall paintings and the establishment of a history of interventions. This background information is fundamental to understanding the causes and mechanisms of deterioration affecting the site today in order to develop, test, and implement appropriate preventive strategies and stabilization treatments to ensure long-term preservation.

Physical and Conservation History

Cave 85 lies at ground level to the north of the Nine-Storey Pagoda (cave 96). It is adjacent to cave 86 to the south and cave 84 to the north; caves 242 and 243 are on the tier above (fig. 1). The cave was created between 862 and 867, during the

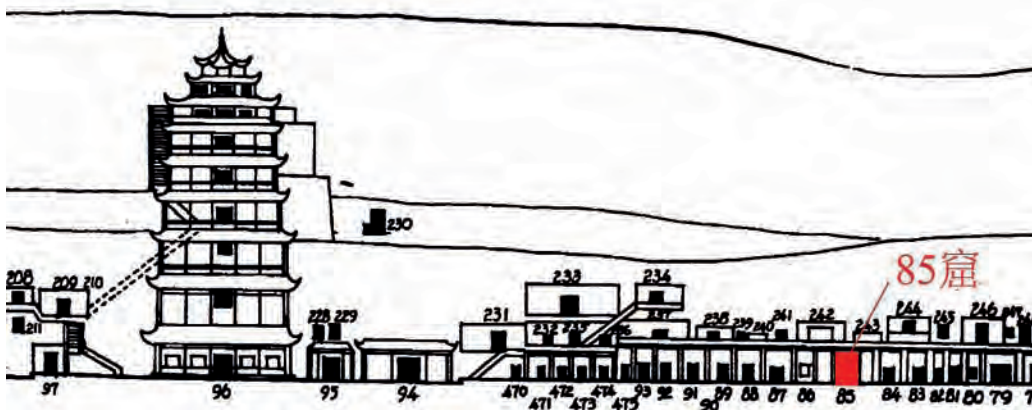


FIGURE 1 The location of cave 85.

late Tang dynasty. Later, in the Five Dynasties period and the Yuan dynasty, the entrance and corridor walls were redecorated. It is one of the larger caves at Mogao, with 316 square meters of painted plaster extant. The cave is divided into three parts: antechamber, corridor, and main chamber (fig. 2). The ceiling of the main chamber is in the shape of a truncated pyramid; and there is a large altar with three sculptures in the main chamber. Before it was given its current designation, the cave was referred to as C60 by Zhang Daqian,¹ as P092 by Paul Pelliot,² and as cave 129 by Shi Yan (Shi Zhangru 1996: 104–6).

In the 1950s large-scale plaster repairs were carried out on the lower part of the four walls of the main chamber, part of the west wall, the lower part of the south and north walls of the corridor, and the upper and lower parts of the west and north walls of the antechamber. In 1957 and 1958 reinforcement work of the cliff face was started in the zone of caves 78–93 on the ground level, which includes cave 85, and caves 237–48 on the second tier.³ Pillars of stone and bricks were built up to support a new facade to protect the cliff face and to accommodate stairs and walkways (fig. 3). At this time, the floor of cave 85 was paved with concrete.

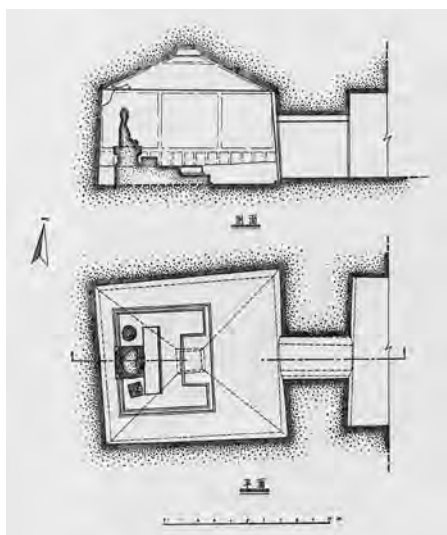


FIGURE 2 Cave 85 in plan and section. The cave is divided into three parts: antechamber, corridor, and main chamber.



FIGURE 3 Cave 85 during construction of facade and walkways (1957–58). Pillars were built in front of the cave to support a wooden walkway and provide support to the fronts of caves 242 and 243.

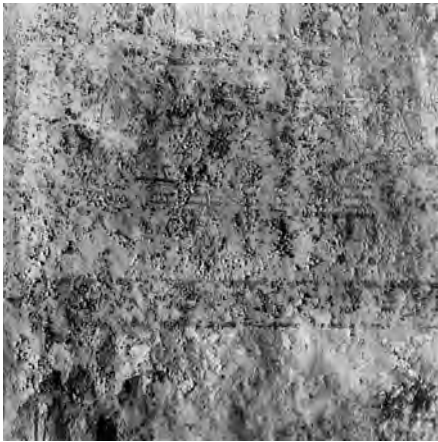


FIGURE 4 Flaking on the east wall of cave 85 (1973).

Archaeological excavation revealed that there were two periods of platform remains that once supported the cave 85 temple front (Pan Yushan, Ma Shichang, and Dunhuang wen wu yan jiu suo 1985: 22–26). The lower, larger platform was built in the Five Dynasties, while the upper platform was built on top of this as a renovation of the cave temple front during the Yuan dynasty.

A condition survey undertaken in cave 85 in 1973 showed that flaking of the paint layer was a serious problem on the southern and northern parts of the east wall of the main chamber (fig. 4), as well as toward the rear, west end of the cave, including the west wall and ceiling slope and western ends of the south and north walls and ceiling slopes. As a result, in 1974 a wooden entrance door to the cave was installed, and 186 square meters of flaking paint and separated plaster were treated. An aqueous mixture of PVA (1.5%) and PVAC (2%) was used as an adhesive in a ratio of 4:1 by volume (Duan Xiuye and Sun Hongcai 1990: 92–94). The adhesive was first injected behind the flakes and then gently pressed back and relaid with brushes and cotton balls. After this operation, PVA (2%) and PVAC (3%), in a ratio of 4:1, were sprayed on to consolidate the surface.

The detached paintings were pinned with two different kinds of anchors (or cross braces), one made of steel (fig. 5) and the other made of poly(methylmethacrylate) or acrylic glass. Steel anchors were used throughout the cave, one on the northern part of the east wall, two on the west wall (the upper parts of the north and south ends), and five in the corridor; two acrylic glass anchors were used on the eastern part of the north wall. The anchors were soon found to be an imperfect solution to the problem of detach-

ment as they sometimes caused cracking in the earthen plaster when inserted and they created stress in the painting around the anchor.

In the mid-1980s, in preparation for the opening of the cave to visitors, movable glass screens were installed in the cave to prevent touching of the wall paintings, the concrete floor of the cave was covered with concrete tiles, and the wooden entrance door was replaced with an aluminium alloy louver door.

In 1998 a severe episode of exfoliation—flaking of the paint, ground, and fine plaster layers—occurred in cave 85. This was associated with high ambient humidity after extended rainfall. Emergency treatment, which involved microgrouting with a clay slurry, was undertaken by the DA-GCI team to readhere and re-lay areas of exfoliation.

Summary of Interventions

The history of interventions in cave 85 indicates that since the 1950s the wall paintings have undergone three major periods of treatment: 1950s, 1970s, and 1998. These interventions have included plaster fills of areas of loss, reattachment of painted plaster that had separated from the rock walls, flake fixing of the paint layer, and, most recently, treatment of exfoliation. The repeated cycles of treatment—approximately every twenty-five years—and the corresponding continued loss of the painting indicate ongoing deterioration in cave 85 and failure to mitigate the mechanisms of deterioration.

This is clearly demonstrated by looking at condition records that show, in 1974, a grayish plaster repair used to fill



FIGURE 5 Example of the steel anchors used to secure areas of detached painted plaster in cave 85. The anchor was painted to match the decoration of the original painting.



FIGURE 6 Example of the visual glossary for “exfoliation.”

Photographic Survey of the Wall Paintings

Photographic documentation of the painted surface of the cave was carried out in both color and black-and-white. The photographs serve as an archival record of the condition of the cave prior to conservation intervention. The black-and-white prints, 20 by 28 centimeters, were used as base maps to graphically record condition. The images were also used during the project as baseline documentation for monitoring change and to help identify any new losses in the paintings.

Due to the sheer size of the cave, photography was broken down into 532 sections measuring 85 by 110 centimeters (photographed with 5–10 cm overlap on each side). The semirectified

an area of new loss of painting on the west ceiling slope. This loss must have occurred sometime after the 1950s, when all areas of loss were filled with plaster repairs. Likewise, since 1974 two more losses have occurred on the west slope, the most recent in 1996.

Following treatment for flaking in 1974, wall paintings in the antechamber, the corridor, and the front part of the main chamber appear to have remained stable. In contrast, toward the west end of the main chamber, in an area previously treated, exfoliation—a more serious form of paint flaking—developed, and ongoing losses have been recorded.

Survey of Current Condition

In 1998, as part of the DA-GCI collaboration, work began on a comprehensive survey of the existing condition of the wall paintings in cave 85. The survey included photography, graphic documentation, and detailed documentation of the types of deterioration and their distribution.

photographs were taken by positioning the 35 mm camera at a fixed distance (140 cm) from the wall, keeping the film plane parallel to the wall surface. Each photograph includes the date, wall name, and wall section number (using an established section identification system) and gray and color scales. Illumination was provided by two 1,000 W quartz halogen lamps. Light meter readings were taken periodically for consistent illumination. Kodak T-max 100ASA and Kodachrome 64ASA film were used.

Classification of Deterioration Types

During preliminary examination of the wall paintings, team members created a bilingual list of deterioration phenomena to be recorded. This glossary focuses on aspects of condition, original technique, and evidence of previous intervention. The glossary includes both a written description and a photograph of each phenomenon (fig. 6). This visual glossary is an important and useful tool to ensure standardization of the graphic recording process and to facilitate subsequent interpretation.



FIGURE 7 The graphic documentation key.

Graphic Condition Recording

Using the predetermined deterioration categories and legend (fig. 7), deterioration was mapped on transparent paper overlaid on the black-and-white photographic prints at 1:5 scale (fig. 8). Altogether, 523 sections were recorded by hand and are archived at the Dunhuang Academy. Manual graphic documentation was subsequently computerized, using AutoCAD software, to summarize the information on measured line drawings by entire wall and slope (1:20 scale) in order to illustrate general patterns of deterioration within the cave and to provide greater flexibility in the analysis and presentation of data. In addition, a three-dimensional model of the cave was constructed and condition overlaid to show the spatial distribution of deterioration in cave 85 (fig. 9).

Results of the Condition Survey

The main types of deterioration phenomena in cave 85 include the following:

- In-depth deterioration (i.e., of plaster layers) covering collapse with loss of plaster and loss of adhesion



FIGURE 8 Example of the manual graphic documentation carried out using overlays on photographs.

(detachment) between the plaster and the conglomerate rock; and

- Surface or subsurface deterioration (i.e., of paint, ground, and upper plaster layers), which includes blistering and flaking of the paint and/or ground layers, combined lifting of the paint, ground, and upper plaster layers (exfoliation; fig. 10), and surface salt-related deterioration such as disruption, punctate losses, and crater eruptions.

Among these conditions, plaster detachment from the rock and a combination of surface conditions, which include primarily flaking and exfoliation and powdering of the paint layer, were the most serious, resulting in ongoing and visible loss of the painting.

Both in-depth and surface conditions showed a similar distribution pattern throughout the cave on a southeast to northwest axis (on both walls and ceiling slopes), increasing in severity toward the northwest end of the cave and most severe at the upper northwest corner of the cave. In contrast, the east end had noticeably less plaster detachment (with the exception of a large area on the north side of the east wall)



FIGURE 9 Scale model (1:35) of cave 85 with condition overlaid to show the distribution of deterioration.

or surface deterioration; since being treated in the 1970s, this area has remained stable.

In summary, it is clear that all forms of ongoing deterioration progressively worsen in both severity and extent toward the west end of the cave, with a concentration in the northwest corner. Visible surface salt activity also increased toward the west end of the cave.

Conclusion

An understanding of both current and past conditions of the wall paintings in cave 85 and knowledge of past interventions has helped to identify and demonstrate those conditions that are considered most serious and are causing ongoing deterioration. This information, together with the diagnostic investigation, which includes both environmental study and analytical investigation, has been fundamental to understanding the processes and the causes of deterioration affecting the cave today.

Acknowledgments

This paper represents the participation of many more team members, from both the Dunhuang Academy and the Getty Conservation Institute, than the eight authors listed above. In particular, much of the behind-the-scenes work was undertaken by the documentation group of the Dunhuang Academy and the Digital Lab of the Getty Conservation Institute. In addition, the conservation team for the cave 85



FIGURE 10 Area of severe exfoliation of the wall paintings in the northwest corner of cave 85.

project, led by Fan Zaixuan, with conservators Stephen Rickerby and Lisa Shekede, provided expertise in the overall recording process and were helpful in the recording of difficult conditions such as plaster detachment.

Notes

- 1 Zhang Daqian (1899–1983) was an artist who visited the Mogao Grottoes between 1941 and 1943.
- 2 Paul Pelliot (1878–1945) was a French explorer and sinologist who visited the Mogao Grottoes in 1908.
- 3 The construction chart number is Dunhuang Shi Sui 017.

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Causes and Mechanisms of Deterioration and Damage in Cave 85

Neville Agnew, Shin Maekawa, and Shuya Wei

Abstract: Wall paintings in cave 85 at the Mogao Grottoes of Dunhuang show detachment (or separation) of the painted earthen plaster from the underlying rock, making it vulnerable to collapse and various forms of deterioration of the paint layer and substrate. Deterioration correlates with the amount of hygroscopic salts (mainly sodium chloride) in and under the plaster on the west wall backed by the conglomerate rock body of the cliff. The relative humidity for the onset of absorption by the salts is 67 percent, a value frequently exceeded in the cave. Salt enrichment at the cave wall is considered to occur by diffusion of water vapor from the porous rock body. The cave is dry, without evidence of liquid water infiltration from above or through the walls; neither does condensation on the walls occur. Humidity in test holes in a comparable cave exceeds the deliquescence value of salts at a depth of 50 centimeters. The source of water vapor is not definitively known but is likely the deep water table or some distant source. Salt migration to the plaster layer occurs by the phenomena of capillarity and salt “creep” at the evaporative front. The driving force is the humidity differential between the rock body and the cave atmosphere. Historically, during periods of sustained high ambient humidity, as from flooding of the floor of the cave, the rock and atmospheric humidity are believed to have equilibrated, resulting in progressive salt enrichment during subsequent drying phases. Over the 1,100 years since the excavation of the cave cycles of deliquescence and crystallization from intrusion of atmospheric water vapor acting in tandem with humidity in the rock have resulted in the present deterioration. Geologic inhomogeneities and fissures and the cracked and deteriorated plaster likely contribute to the diffusion of water vapor and salt migration. Laboratory experiments have shown the facility with which salt migrates through the rock.

For the future, a stable climate in the cave below 67 percent relative humidity is necessary for its best preservation. This means preventing intrusion of air via the doors during rain or periods of high external humidity, which, in turn, requires closing the cave to visitors when these conditions occur.

This paper considers natural, rather than human-induced, causes of deterioration and damage observed in cave 85. Though the focus is on this cave, the deterioration phenomena generally pertain to other cave temples of the Mogao Grottoes as well. Other papers on cave 85 in the present volume classify and describe the deterioration observed in detail (detachment, flaking and peeling of paint, powdering of the fine plaster, etc.).

Deterioration phenomena at Mogao vary from cave to cave and with vertical distribution on the cliff face: the most severely deteriorated caves are typically at ground level, followed by the uppermost caves, with the best preservation at mid-tier. Cave 85 is located at ground level and has suffered extensive deterioration, particularly on the west wall and the western sides of the north and south walls. In the past, flooding of the floor caused complete loss of wall paintings and earthen plaster to a height of about one meter and enriched the soluble salts content in the exposed conglomerate. This loss and the manifestly poor condition of the entire west wall (backed by the rock of the cliff) are also the most apparent kinds of deterioration in many, but not all, caves at ground level.

At Mogao a latent catastrophic threat is detachment of painted plaster; extensive areas have separated from the conglomerate, and over time many segments have fallen under their own weight, particularly after prolonged peri-

ods of high ambient humidity, most recently in 1996 after several days of rain. The Dunhuang region is rated seismicity degree 6 on the national classification scale (Sun Rujian 1997), and the next temblor will result inevitably in collapse of many detached areas of painting. An earthquake of magnitude 6.5 to 7 on the Richter scale has been predicted for the region (Fan Jinshi 1997).

Deterioration of the earth-based wall paintings is caused by humidity and salts from the rock in and on the painted plaster. Detachment or separation of the plaster from the conglomerate is probably inherent, to some extent, from the time of construction of the cave but is exacerbated by cycles of deliquescence and crystallization of salts at the interface between the rock and the plaster. The present paper endeavors to identify the mechanism of enrichment of salts and areas for further investigation. Other contributions to this volume also address the sources of moisture, and in a sense the present paper attempts to mediate between the views presented by Maekawa and colleagues on the one hand and Tanimoto and colleagues on the other: the former have monitored atmospheric moisture vapor in the cave and in test holes in the rock, whereas the latter emphasize regional geology and local hydrology and the movement of both liquid water and water vapor in the rock as being key.

Salts, Water, and Deterioration

Moisture in caves and tombs in the presence of soluble salts causes great harm. In desert climates, however, in the absence of direct evidence of water seepage, the mechanism whereby salt enrichment occurs at and near the wall surface seems not to be definitively understood. For example, G. Torraca (1984) speculated that salt damage in the tomb of Nefertari in the Theban necropolis was attributable to the growth of crystals due to evaporation after occasional wetting, activated by air circulation in the tomb. Yet the tomb entrance was closed perhaps for three thousand years after the tomb had been looted, and although there is rare flooding in the Valley of the Queens, there is no evidence of liquid water intrusion into the deepest chamber, where salt buildup between the painted plaster and the limestone bedrock was observed to be up to 25 millimeters thick in places. Instead, moisture seeping into the porous rock via joint planes and fissures and diffusing to the tomb as vapor seems probable. How thoroughly the Nefertari tomb was sealed against air exchange with the outside is not known and was apparently not remarked on by Schiaparelli at the time of its discovery

(1904). Air exchange would create a driving mechanism for salt enrichment on the chamber walls.

Tutankhamen's tomb, on the other hand, was hermetically sealed and was reported by Carter to have a close and humid atmosphere when first opened in 1922 (Carter and Mace 1963). The organic artifacts present were in equilibrium both with the internal atmosphere and with the humidity of the surrounding rock, as evidenced by the changes that began immediately on their exposure to the dry external atmosphere. Carter surmised that water had filtered through the permeable limestone from an external source, but he was unable to see locations where water had entered, nor was there evidence of infiltration damage on the wall paintings or buildup of salt as in Nefertari's tomb. Plausibly, the external source provided only water vapor, which periodically diffused through the limestone to equilibrate with the cavity of the tomb and its contents.

At Mogao, in general, with the exception of ground-level flooding and rainwater infiltration in upper-tier caves where erosional thinning and sometimes collapse of the rock of the roof occurred, liquid water is not a factor in deterioration. An observation, however, among many caves that lost their wooden temple facades, it is believed, in the centuries of abandonment after the Ming period, is that windblown sand filled the entranceways, and this caused water to be wicked into the cave during wet periods. Typically, these caves show loss of painted plaster where the wet sand had banked against the walls, quite often extending through the corridor as far as the main chamber.

Hygroscopic salts in porous materials (stone, ceramics, earth- and clay-based artifacts) cause deterioration through cycles of deliquescence and recrystallization. Values of RH_{eq} (the equilibrium relative humidity generated in a closed vessel by a saturated aqueous solution of a pure salt at a given temperature) are well known (e.g., for NaCl, it is 75%), but in mixtures and in those salts that form crystalline hydrates the situation is complex (Price 2000). The exact mechanism of deterioration by salts is still not settled, but it seems generally true that damage occurs when they crystallize. The assumption that environmental humidity less than the RH_{eq} of a soluble salt will not result in damage is in doubt. Studies (Nunberg and Charola 2001) have noted deterioration from changes in relative humidity between 43 and 55 percent using sodium chloride and sodium sulfate and mixtures of both in porous materials. Presumably interstitial capillary condensation is the phenomenon whereby some of the salts present are brought into solution well below their RH_{eq} . Weight

changes in the test materials of less than 0.5 percent, in the case of NaCl, were observed and damage was small, but the finding may be significant to damage over long periods and should be corroborated by further work and for relevance to sites such as Mogao.

Conservation Issues

Since it is impossible, in fact inadvisable, to attempt to extract even a significant fraction of the soluble salts from the Mogao wall paintings (see, eg., Cather 2003), environmental control of caves at risk must be the damage mitigation method of choice in the long term. Conservation treatments, including partial salt reduction as in poulticing, require understanding of the cause-and-effect relationship between humidity and hygroscopic salts both at a general level and, preferably, in detail, including rates of moisture-mediated deterioration in salt-enriched substrate. For example, attempts at desalination of painted brick vaults in a church in Denmark by RH control have been made. These were not effective for a variety of reasons (Larsen 1999). Rates of deterioration will depend on the rate of adsorption of water vapor by salts, which in turn depends on crystal size, air movement, and porosity of the plaster and rock. Thus collapse of detached plaster in cave 85 occurred after some five days of rain when sufficient moisture had been adsorbed to affect the strength of the plaster through dissolution of salts and increased plasticity of clay. The plaster itself (36% sand, 45% silt, 19% clay) was derived from Daquan River sediment and contains, in the clay fraction, 30 percent swellable clays (illite/smectite) (Austin 1998). Laboratory experiments show detectable mass increase in salt-laden conglomerate after about three hours at 85 percent relative humidity.

Key Questions

To understand the situation at the Mogao Grottoes site, a number of questions were posed:

- In the desert climate of Dunhuang what is the source of moisture in cave 85—is it entirely atmospheric, or does hydrologic (i.e., geologic) water also play a role?
- What is the critical relative humidity at the walls in cave 85 for deliquescence of salts (mainly NaCl), and how long does it take to absorb moisture? Does capillary or interstitial condensation play a role?
- How did salt enrichment at the conglomerate-plaster interface, and in the plaster layer, occur over time; that is, what is the origin and what is the mechanism of enrichment?
- Why are some caves more deteriorated (due to more salts in the plaster) than others?
- Has atmospheric condensation occurred on the wall paintings?

From the salt distribution in the plaster of the west and east walls of cave 85 (Wong et al., this volume) it is apparent that there is more salt in the west wall (av. 3.4 wt%), which shows severe deterioration, than in the east wall (av. 1.2 wt%), which is much less damaged. Cave 98 is another large ground-level grotto with a distribution of deterioration and salt content (av. 3.9 wt%) similar to that of cave 85. By contrast, exterior, exposed conglomerate contains 0.15–0.77 wt% (av. 0.3) salts along a vertical profile of the cliff. The inference is that enrichment of salt occurred by extraction from the rock body. The west wall, excavated into the bulk of the mother rock, would have a far larger reservoir of salt and water vapor than the east wall, which forms the outer face of the cave. One would expect, therefore, that as a general rule the west walls of caves would show greater deterioration than the east walls. This is generally true. Cave 61, however, with less salt (av. 1.5 wt%) than cave 85, is not so seriously deteriorated on its west wall as are caves 85 and 98, though it is quite close to cave 85 and is topographically lower in elevation as well. Furthermore, caves 85, 98, and 61 were all historically flooded. A hypothesis about salt enrichment must endeavor to explain this. This point is returned to later.

For salt enrichment to occur at the surface of the wall, moisture is needed. As mentioned, there is no evidence that this was liquid water; instead, water vapor is implicated. At the scale of the site, consistent baseline concentration of salts in the rock of the cliff face (both vertically and horizontally) is unlikely, however, particularly where geologic inhomogeneities, both petrological (e.g., lenses of sandstone in the conglomerate) and structural (cracks), occur, as discussed below.

Sources of Moisture

There are a number of possible sources of moisture to have mobilized salts and that contribute to deterioration:

- Cave construction: Water from the wet earthen plaster and prewetting of the walls prior to plaster-

ing. There is no historical information on this. It would seem improbable that a single event, such as wet mud plaster, could lead to 4 wt%, or more in some locations, of salts being extracted from the relatively low (average 0.3 wt%) natural concentration in the exterior conglomerate.

- Geologic: Water vapor content in the porous rock that increases to saturation at 1 meter (figs. 1, 2), as shown in two monitoring holes in the west wall and one in the floor of cave 98 (wall holes were 1.5 meters above the floor, 0.5 meter from the north and south walls, and 1.3 meters deep; the floor hole was 1.5 meters from the west and east walls and 1.3 meters deep). Even though the water table is at least 20 meters deep, according to the Dunhuang Academy, humidity in the floor hole was similar to that observed in the walls. The moisture content at all areas of the conglomerate along the cliff face is unlikely to be the same because of fractures in the rock, intersections with fault planes, lenses of sandstone with different water vapor permeability, and areas of greater porosity, where the conglomerate is inhomogeneous, allowing more rapid diffusion of water vapor.

- Meteorologic: Intrusion of external humidity via the entrance to the cave.
- Flooding and irrigation: Past flooding of the Daquan River, manifested as loss of painted plaster above the floor level, is evident in many ground-tier caves, often to a height of about 1 meter. As mentioned previously, some cave entrances at ground level were also filled with windblown sand, and this too resulted in loss of painted plaster when sand heaped in the entrance and the corridor was wetted. Irrigation of the trees growing in front of the grotto zone has frequently been cited as a cause of moisture intrusion by means of lateral migration into the caves, but this has been refuted by the work of Maekawa et al. (this volume). Tanimoto et al. (this volume) disagree based on resistivity measurements outside the caves.
- Condensation: Environmental data of many years show that the dew-point temperature in the caves is not reached in the summer, and thus wall condensation can be discounted (Maekawa et al., this volume).

Humidity caused by visitors to the caves is unlikely to contribute to salt enrichment, though visitors' effect on

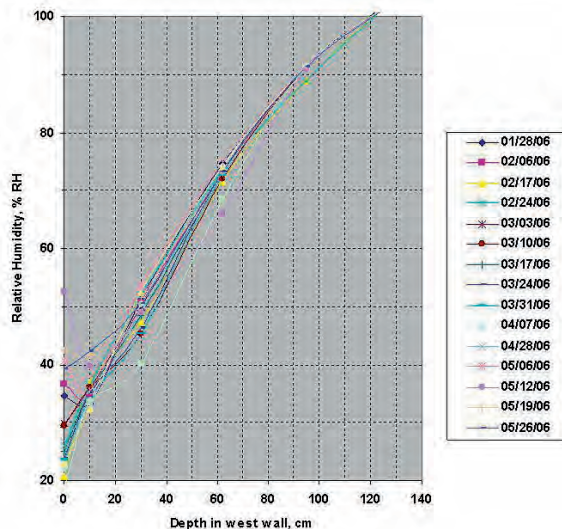


FIGURE 1 Relative humidity in the conglomerate of the west wall of cave 98 as a function of depth and season. Fluctuations due to the cave environment extend to a depth of 10 centimeters. Individual sensors in the monitoring hole were well isolated from each other.

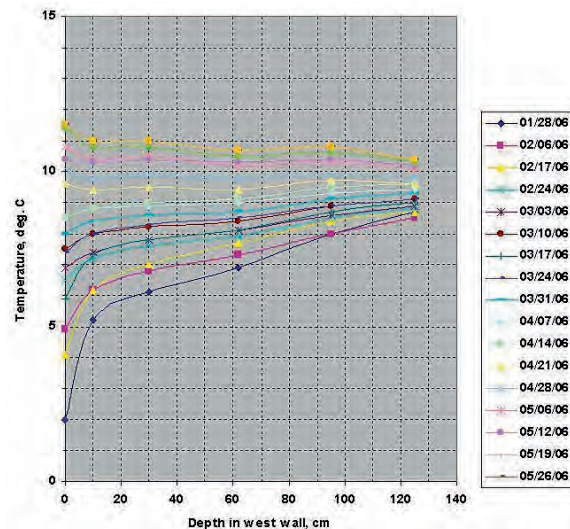


FIGURE 2 Temperature in the same monitoring hole shown in figure 1. Seasonal temperature variations extend more than 100 centimeters into the rock.

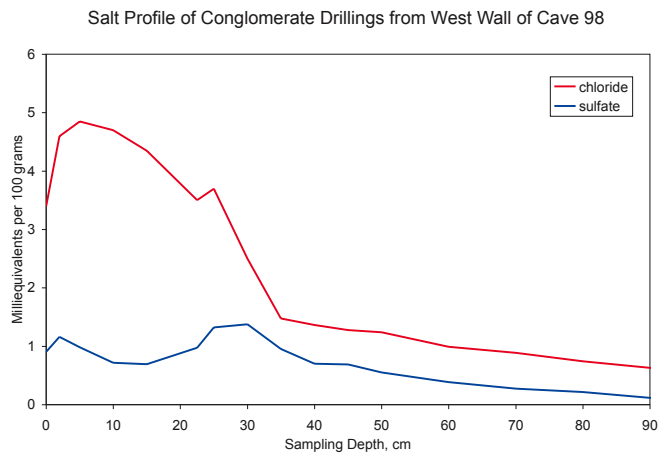


FIGURE 3 Chloride and sulfate ion distribution with depth in the same monitoring hole shown in figures 1 and 2. (Data provided by Dunhuang Academy)

humidity (about 5% increase over ambient) is real. However, the visitor carrying capacity study for the grottoes has shown that this effect can be neglected (Demas et al., this volume).

Interpretation

Salt migration and accumulation at and near the surface can only occur as a result of dissolution of the salt. Differences between caves in amount of salts and in degree of deterioration need be accounted for. Historical flooding of the floor alone cannot explain the lower salts content in cave 61 or the lesser salt damage observed. Maekawa's data show that the cave 85 walls are also "conditioned" in summer by intrusion of high external humidity, presumably because of moisture uptake by salts and plaster. This points to external humidity as being the cause of the marked difference in the condition of the wall paintings observed in caves 85 and 61.

It is proposed that the above observations can be explained both by geologic moisture vapor diffusion through the rock and by intrusion of humid meteorologic air via the cave entrance. The actual process of salt enrichment suggested is transport of salts in solution through capillary condensation and migration of solution close to the rock surface, where a zone of enrichment occurs due to crystallization. Figure 3 shows this accumulation in the conglomerate in cave 98. Salt creep is an everyday observation (fig. 4). It is essentially this process that is being proposed for salt accumulation at the cave wall via the intrusion of meteo-

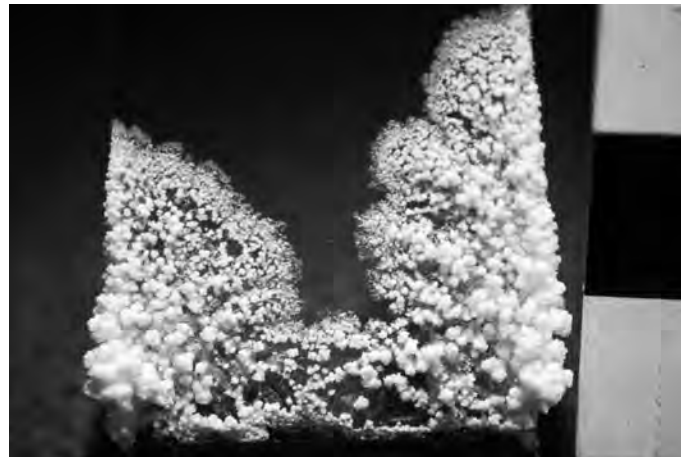


FIGURE 4 Creep of sodium chloride up a microscope slide as the solution evaporated.

rologic moisture and its adsorption by the plaster and rock during periods of high and sustained humidity. Pühringer (1983, 2002a) has proposed a possible mechanism for water vapor-induced migration of soluble salts in porous substrates during atmospheric humidity cycling. This is based on his explanation of the phenomenon of salt creep (Ginell 2005). Over the millennium and more since the caves were created, these two processes have abetted each other, leading to the accumulation of salt. It is shown in laboratory studies, discussed below, that salt migration to the evaporative surface can occur by a humidity differential. Once enrichment has occurred at the plaster-to-rock interface meteorologic

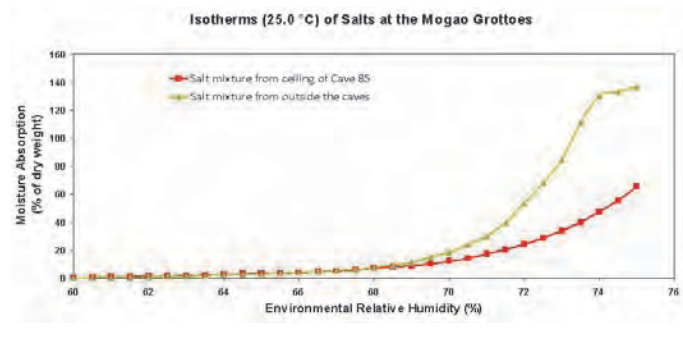


FIGURE 5 Weight increase as a function of relative humidity of salt mixtures sampled from the interface between the plaster and conglomerate in cave 85 and taken from external conglomerate.



FIGURE 6 Sodium chloride migration experiments. (a) Conglomerate; (b) conglomerate with a layer of clay plaster, half of upper surface painted with pigments found at Mogao.

humidity dominates as the active mechanism of deterioration. This begins to occur with each high relative humidity event that is sustained for more than an estimated four to six hours above the value of 67 percent relative humidity (fig. 5).

The difference between caves 85 and 61 is best accounted for in terms of geologic inhomogeneities in the west walls, the former having more fractured rock and stratigraphic differences such as highly porous sandstone lenses intercalated with the conglomerate. It does not seem possible to resolve the question of the geologic role behind the plaster surface without further investigation.

Laboratory Studies

Salt (NaCl) migration experiments were undertaken on both the conglomerate and the sandstone from lenses that occur throughout the former. Experiments used a humidity differential across test samples. Briefly, small samples (about 25 millimeters thick, roughly square) were embedded around four sides in wax and sealed into a glass container (fig. 6). The samples had salt applied to the undersurface and were then alternately equilibrated in a chamber at two relative humidities (first at 85% and then at 43% on the two opposed faces) until salt appeared on the upper surface (fig. 7).

Results were as follows. Salt migrates through conglomerate with facility, appearing on the upper surface after five complete cycles. Sandstone samples, while equilibrated

ing much more rapidly than the conglomerate, show a salt distribution throughout the body of the sample but without the appearance of salt on the upper surface. The difference in salt profile between conglomerate and sandstone suggests that pore characteristics play a role in transporting salt. The greater abundance of fine material in the conglomerate may enhance capillary transport, while the larger pores in the sandstone allow rapid penetration of humid air and

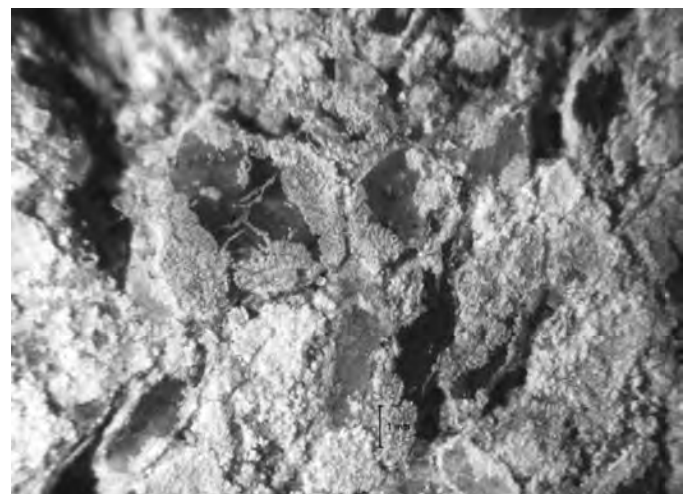


FIGURE 7 Sodium chloride crystallization on upper surface of conglomerate. Note salt creep around edges of larger grains.



FIGURE 8 Salt eruption on the unpainted clay plaster.

distribution of salt. Total porosity and pore size distribution are yet to be determined for conglomerate and sandstone, however. It would be informative to know whether sandstone lenses occur on the west wall of cave 85; however, the plaster on this wall is intact (with the exception of the base, where it has been lost) and a noninvasive technique of sufficient sensitivity is not available. Sandstone would transport less salt to the surface but is more permeable to water vapor migration into the bulk of the rock, thereby mobilizing more salt from the subsurface zone of enrichment.



FIGURE 9 Well-formed cubic crystals of sodium chloride below the paint layer (also at the clay-conglomerate interface).

A further relevant observation was that in samples of conglomerate that were overlaid with clay plaster and painted with pigment and binding medium, replicating those in the caves, sodium chloride eruption occurred on the clay surface (fig. 8) but was not observed on the paint surface. Instead, on examination of lifted paint flakes, euhedral crystals of salt were observed (fig. 9). Only in one instance, after five cycles, did the beginning of damage to the paint layer occur. Moreover, accumulation of salt at the conglomerate-clay interface was observed. In the caves this is a probable contributor to plaster detachment because of disaggregation and fretting of the rock from cycles of deliquescence-recrystallization. In other words, conglomerate may recede behind the plaster by salt-induced fretting; it is not buildup of salts that detaches plaster.

Discussion

Note that distinction is made between historic and recent deterioration. Most likely serious damage occurred, or the conditions were established for subsequent deterioration, during the several centuries of abandonment. Moisture intrusion from flooding and sand would have resulted in prolonged periods of high humidity. As atmospheric drying took place salts moved by creep from within the rock to the plaster, resulting in separation from the conglomerate, disruption of the plaster, and other forms of salt-induced deterioration.

Laboratory experiments show that it is possible to cause salt to migrate through porous media (conglomerate, sandstone, earth-based plaster) with cycles of humidity differential above and below RH_{eq} of the salt. To what extent is this an accurate simulation of the situation in cave 85 and other caves? To what extent does atmospheric humidity above the value of 67 percent relative humidity penetrate through painted earthen plaster that is clay rich and diffuse into the conglomerate? The conglomerate sample with clay plaster on top took about twenty days in the laboratory to equilibrate across the sample when the differential was 85 and 43 percent relative humidity. This was a static air experiment in a closed chamber. In the case of the caves, the penetration of humid air should be faster because of air movement, cracks in the painted surface, and the already salt-deteriorated plaster. Just how fast and how deep the “front” of humid air would penetrate through and into the mother rock is not known exactly, though the test holes in cave 98 showed seasonal RH/T variations to a depth of

10 to 15 centimeters. To bring to or near the surface the quantities of salts seen in the west wall of cave 85 presumably the penetration would have to be sufficiently deep to reach the zone of salt enrichment (in cave 98 where the clay plaster has been lost on the west wall, the maximum in chloride content is about 5 to 10 centimeters from the surface, with sulfate at 25 to 30 centimeters) and require extended periods of high humidity in the cave, as well as cycles of high and low humidity. Given, however, the circumstances of the age of the cave (1,100-plus years), evidence of past flooding, and occasional periods of extended rainfall, the conditions and time required for salt migration and enrichment at and near the surface are likely to have been met.

Conclusion

This paper has been concerned not with the mechanisms of salt-induced deterioration of wall paintings in cave 85 but rather with understanding the conditions and processes by which the low concentrations of natural salts in the conglomerate moved to and became concentrated close to the wall paintings, mainly at the rock-plaster interface, by the interplay between water vapor from the rock body and meteorologic humidity.

The findings are pertinent both to how the salt has migrated and accumulated on the west walls and at what interfaces it accumulates, that is, conglomerate to clay plaster; clay plaster to paint layer. But questions still remain, and the discussion above has been simplified by considering essentially only sodium chloride in the laboratory experiments, whereas analysis of the salt species present in Mogao conglomerate indicates a range of other ionic types (mainly sulfate), which contribute to a lowering of the deliquescence RH but may also contribute to accelerated deterioration.

The purpose of this paper has been to understand qualitatively the complex interactions between water vapor (from both the atmosphere and the rock body), hygroscopic salts in the conglomerate and plaster, and the thin surface of paint that led to the deterioration seen today. Discussion of the cause and effect of the phenomena is clearly provisional, and research at a fundamental physicochemical level is needed. For effective preservation of the wall paintings at the Mogao Grottoes and the many other similar sites in China and along the Silk Road, a combination of environmental controls and treatment and salt reduction techniques must depend on a complete understanding and diagnosis of all the deterioration mechanisms, their causes and rates.

Further Work

The physics of water and salt transport in porous media is exceedingly complex, as indeed is the mechanism of deterioration of stone by salts. Many studies have been undertaken and the literature is extensive (Ginell 2005). In addition to the work of Pühringer (2002b), there are useful papers in the volume edited by A. E. Charola (2005). In the past decade or so new tools have been applied to the problem, particularly nuclear magnetic resonance (see, e.g., Petkovic 2005). Other work of relevance, though technical, has been published by F. A. L. Dullien (1979). D. Camuffo (1995) provides a concise overview of stone weathering; more accessible to the conservator is the paper by Bionda (2004).

Most published work in the conservation literature has been concerned with mechanisms of deterioration of stone by salts and to a much lesser degree with the salt enrichment process at the surface and subsurface. A generalized, nontechnical explanation of conditions under which salt enrichment occurs for particular rock types, salt mixtures, environmental conditions, and so forth is necessary to aid conservation practitioners in diagnosis and development of remedial and preventive measures.

In the particular case of the Mogao Grottoes further field investigations on salt profiles, water vapor sources, and subsurface zones of enrichment are needed to corroborate or refute the suggested mechanisms proposed here and in the debate regarding the origins of moisture.

Acknowledgments

The authors are grateful to colleagues at the Getty Conservation Institute, Lorinda Wong, Francesca Piqué, and Michael Schilling, who participated in the cave 85 project. Their commitment to the project, helpful discussion and comments, and analytical and environmental results used in this paper are much appreciated. William Ginell extensively reviewed the literature on moisture and salt transport in porous media, and Eric Doehne provided scanning electron microscope images and comment on the characteristics of the rock types used in the laboratory experiments. Staff of the Conservation Institute of the Dunhuang Academy, Chen Gangquan, Su Bomin, and Fan Yuquan, generously provided chemical data for the conglomerate salts from the cliff face and test holes in cave 98 and shared their detailed knowledge of the site. Wang Xudong kindly approved the request to drill two holes in the west wall and one in the floor

of cave 98 in order to monitor humidity and temperature and determine salts content by analysis of the cuttings.

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Methodology for the Conservation of the Wall Paintings in Cave 85

Francesca Piqué, Lorinda Wong, and Su Bomin

Abstract: *The extent and severity of the deterioration of the wall paintings in cave 85 at the Mogao Grottoes exemplified the need for a methodological approach to their conservation, one that is based on an understanding of the materials, technology, and causes of deterioration and that favors minimal intervention and preventive conservation. In the past, wall painting conservation at Mogao consisted of repair treatment carried out without addressing the causes of deterioration. To address causes of deterioration it is necessary to follow a methodology of investigation, assessment, and diagnosis prior to the development and implementation of preventive measures and stabilization treatments. The collaborative project between the Getty Conservation Institute and the Dunhuang Academy for the conservation of the wall paintings in cave 85 has been developed as a model case study of the methodology advocated in the Principles for the Conservation of Heritage Sites in China. This paper illustrates the application of the conservation methodology through the different phases of the program.*

The Getty Conservation Institute (GCI) has been collaborating with the Dunhuang Academy (DA) since 1989 to address sitewide conservation problems such as sand migration and erosion. Since 1997, in the second phase of this collaboration, the focus has been on conserving the wall paintings and sculpture of cave 85, using the methodology of the *Principles for the Conservation of Heritage Sites in China* (the China Principles), national guidelines developed in a three-way partnership between China's State Administration of Cultural Heritage, the Getty Conservation Institute, and the Australian Heritage Council and issued by China ICOMOS.¹ Senior leaders at the Dunhuang Academy participated in

writing the guidelines and their other applications, notably the Mogao site master plan (see also Fan Jinshi, this volume) and the cave 85 conservation project.

The challenges of preserving the site's 492 decorated cave temples are linked both to its large size and to the complexity of the conservation problems. One difficulty is the nature of the earthen plasters of the polychrome paintings and sculptures, which differs from that of the lime-based plasters that are more familiar to the conservation world. Earthen-based paintings are generally water-sensitive, and therefore the technology and methods developed for treating lime-based paintings are often not appropriate. Because there is relatively little literature on the treatment of earthen-based wall paintings and sculpture, a large component of the project focused on treatment research specific to earthen-based wall paintings.

Cave 85, a late Tang dynasty cave excavated and decorated between 862 and 867 C.E., was selected as representative of the severe and unresolved conservation problems affecting the wall paintings at the Mogao Grottoes (fig. 1). It is one of the larger caves at the site: approximately 350 square meters of painted surface with fourteen illustrated sutras in the main chamber and three sculptures in the central altar (see Wang Jinyu, this volume).

The cave is situated at ground level, midway along the 1.6-kilometer-long cliff face, just north of the prominent Nine-Story Pagoda. The cave temples were excavated into the cliff face, which is composed of soft conglomerate rock. The walls were then plastered and smoothed over with earthen-based plasters and painted with inorganic and organic pigments (for detailed information on cave 85 painting technique, see, this volume, Shekede et al.; Schilling et al.) (fig. 2).



FIGURE 1 Cave 85 (upper level, west side ceiling) during early stages of the project.
Credit: J. Paul Getty Trust

Methodology

The cave 85 conservation plan was developed following a methodological approach based on the China Principles. The philosophical and conceptual approach depends on a statement of the cultural values and significance of the cave in the context of the site as a whole (Demas 2002). Preservation of the cultural significance is the ultimate objective of the project.

The process for the collaborative conservation of cave 85 consisted of five phases: information gathering, assessment, testing and development, implementation, and monitoring and maintenance (table 1). Two field campaigns of joint work, discussion, and information exchange were held at the site per year, in spring and fall. Between campaigns the GCI and the DA teams worked on agreed-on tasks with regular communication, following up on the results of the campaign and in preparation for the next one. Additional training of DA staff took place annually at the GCI in the areas of documentation, treatment testing, instrumental analysis, and environmental investigation. The phases of the project are described below.

Information Gathering

This phase involved research, compilation, and review of background information. An information management system was developed to allow systematic storage and retrieval of project data, including documentation, results, reports, and images (see also Wong et al., this volume). The system allowed quick access to data and facilitated sharing of information between teams.

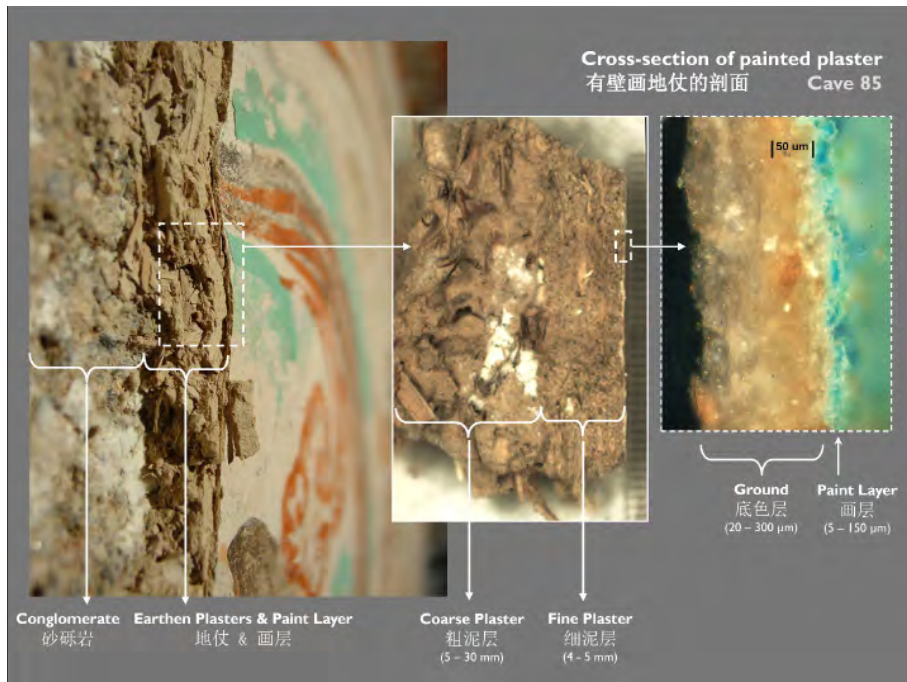
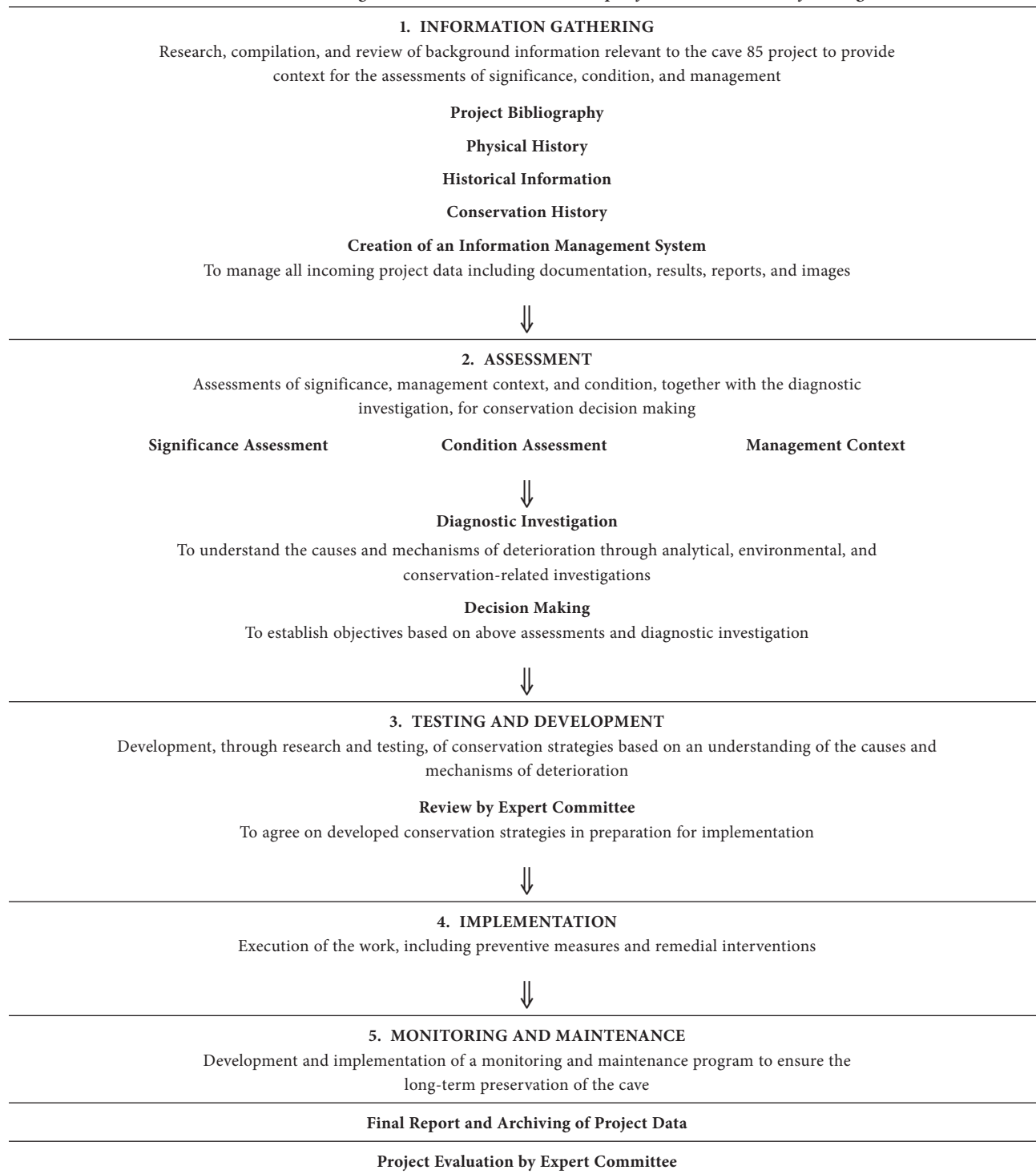


FIGURE 2 Stratigraphy of the painted plaster in cave 85.
Credit: J. Paul Getty Trust

Table 1 Conservation Process for Cave 85, Mogao Grottoes, Based on the *Principles for the Conservation of Heritage Sites in China*



Project Bibliography

A bibliography was started at the beginning of the project and was regularly updated. It covers literature on the site and information on methods and materials used to make and to conserve earthen-based wall paintings. The bibliography exists in hard copy, and an electronic version is being developed as a database searchable by keywords.

Background Information

Information relevant to cave 85 was researched, compiled, and reviewed using archival records, historic photographs, and oral sources:

- Description of the site, including information on geology, hydrology, and climate;
- Information on the physical history and historic context of the site and cave 85, including historic photographs;
- Description of cave 85 and its wall paintings and sculptures, including information on construction techniques and Tang dynasty iconography;
- Conservation information on previous treatments, including type and extent, and generally about conservation practices at the Mogao Grottoes; and
- Visitation history of cave 85, that is, when it was open and closed to the public.

Examination and synthesis of material collected in this phase provided an understanding of the physical and historical changes to the site and their impact on the cave.

Assessment

The assessment phase was central to the methodological process and included research necessary to make decisions about the conservation and use of the cave. This phase involved an understanding of the significance and values of the cave, the management context of the site as a whole, the condition of the wall paintings and sculpture, and a diagnostic investigation of the causes and the mechanisms of deterioration.

Significance

Assessment of significance and the resulting *Statement of Cultural Values and Significance* take into consideration the artistic, historic, social, and scientific values of the site and specifically of cave 85. Significance assessment is an essential component of any project to ensure that the values and sig-

nificance are preserved unimpaired (see Wang, this volume). Preservation of cultural significance is the ultimate objective of the project.

Management

Management assessment involves identification of the constraints and opportunities that may affect the ability of management to preserve and protect a site. The management assessment, undertaken by the project managers, consisted of the following:

- Understanding the management structure responsible for the conservation and maintenance of cave 85; and
- Establishing the responsibilities of the GCI and DA in terms of expertise, budget, and time necessary for the completion and sustainability of the project.

Condition

The condition assessment provided a comprehensive record and understanding of the condition of the wall paintings and sculpture through identification and documentation of the types and distribution of deterioration. This involved the following:

- Detailed visual and instrumental examination of the paintings and sculpture;
- Comprehensive photographic survey of the paintings and sculpture;
- Creation of an illustrated glossary of condition terms; and
- Graphic documentation to map types and distribution of the most significant types of deterioration.

Deterioration phenomena observed in the cave included surface deterioration, such as exfoliation, flaking, and “punctate” eruption of the paint layer, and subsurface deterioration, such as plaster detachment. These phenomena are common in other caves at the site. Deterioration was markedly more severe toward the northwest side of the cave, that is, the rear of the cave (see Xu Shuqing et al., this volume) (fig. 3).

Diagnostic Investigations

The aim of the diagnostic investigations was to understand the causes and mechanisms of deterioration of the wall paintings and sculpture (see, this volume, Agnew et al.; Maekawa et al.). This involved:



FIGURE 3 Details of similar scenes taken from the east and west ends of the south wall illustrating the difference in condition: (a) the paintings at the east, toward the front of the cave, are in near-pristine condition; (b) at the west, toward the back of the cave, they are in poor condition (loss of paint layer and color change).

- Identification of active deterioration processes;
- Establishment and testing of hypotheses of causes and mechanisms of deterioration through
 - study of original and added materials as part of the analytical investigation; and
 - monitoring of exterior and interior climate as part of the environmental investigation.

Identification and Determination of Active Deterioration. The study of documentation collected on the physical history of the cave was useful for identifying active deterioration. When there is active deterioration, repair and strengthening of the object without addressing the causes and mechanism of the deterioration are only a temporary remedy that often causes more damage in the long run (Cather 1999). The two principal types of ongoing deterioration found in cave 85 were exfoliation and detachment. Both conditions had been treated previously and had recurred.

- *Exfoliation:* lifting of paint, ground, and upper plaster layers (fig. 4). This seems to be associated with previous treatments (in the 1970s) for flaking in which polyvinyl acetate and polyvinyl alcohol fixatives were used. Over time, these treatments failed and the conditions returned in most areas.



FIGURE 4 Exfoliation, the lifting of paint, ground, and upper plaster layers, apparently exacerbated by treatments for flaking (in the 1970s) using polyvinyl acetate and polyvinyl alcohol fixatives. The continued loss of painting indicates that this problem is ongoing, most notably at the northwest end of the cave.



FIGURE 5 Detachment, followed eventually by collapse, is a widespread problem. Here, fragments of painted plaster lost from the west slope in 1996 near an anchor installed in the 1970s. Credit: J. Paul Getty Trust

The loss of paint, apparent by comparison of current condition and historic photographs, shows that this problem is ongoing, most notably at the northwest end of the cave.

- *Detachment*: loss of adhesion between earthen plaster and conglomerate rock body. This condition has been a long-term problem and is pervasive at the site. In the 1970s pinning with cross-bracing was used to hold the plaster in place in cave 85. However, this did not address the problem, and it was only a temporary solution. In 1996 a large piece of painted plaster fell from the west slope of the cave during a period of heavy rain (fig. 5). The loss occurred near a metal anchor used to treat the detachment problem thirty years ago.

Paint exfoliation and plaster detachment cause loss of painting on a large scale and therefore are the most severe problems that require intervention. Areas of detachment and exfoliation increase in severity toward the rear, northwest end of the cave, where large losses and anchors indicate a history of problems. Areas of detached plaster are prone to fall under gravity alone, or they are precipitated by seismic shock (Dunhuang is a seismic area) or extended periods of high humidity when hygroscopic salts have absorbed water, causing a weight increase of the plaster.

Cause and Mechanism of the Active Deterioration. The topographic distribution and the specific conditions observed

suggested a deterioration mechanism associated with salts and humidity. It was necessary to obtain a good understanding of the salts present in the paintings and the possible sources of moisture and of its fluctuations in the cave.

Analytical Data. The focus of the diagnostic investigation was the identification and quantification of the soluble ionic species and their distribution within the paintings (see also Schilling et al., this volume). An extensive salt survey of the soluble ion content in the plaster found direct correspondence between the deterioration distribution and salt content, that is, higher ion content toward the west end of the cave, where the condition of the paintings is poorer. The most common salt identified was sodium chloride.

Environmental Data. Environmental data indicated that the cave's microclimate was affected by the climate at the site but that no liquid water was present in the cave (see also Maekawa et al., this volume). In the desert environment the air is generally dry in winter (10–20% RH) and more humid in summer (50–70% RH). Summer rain events can cause the cave's humidity to rise to 80 percent relative humidity or higher. Laboratory experiments show that earthen plaster from the cave begins to absorb moisture at about 67 percent relative humidity. Repeated cycles of water absorption, salt dissolution, and subsequent recrystallization can lead to deterioration; or at prolonged exposure to high relative humidity, to collapse of detached plaster.

The combination of conservation, analytical, and environmental information allowed the formulation of deterioration hypotheses. Deterioration is related to the soluble salts present in the plaster, mainly sodium chloride, and the fluctuations of the cave's relative humidity. Pure sodium chloride absorbs water vapor at a relative humidity of 75 percent and dissolves, a process called deliquescence. Studies have shown that mixtures of different salts, such as occur in cave 85, deliquesce below their individual equilibrium relative humidity values (Nunberg and Charola 2001; Price and Brimblecombe 1994; Sawdy 2003).

The type of deterioration produced by soluble salt activity is dependent on the zone of crystallization: when occurring at the interface between plaster and conglomerate, crystallization can cause detachment (and collapse) of the earthen plaster; when just at the surface, it can cause surface deterioration. Exfoliation, one of the surface deterioration phenomena observed, seems to be also related to both humidity fluctuations and the application of vinyl dispersions (polyvinyl alcohol and acetate) applied in the 1970s to consolidate and fix the painted surface. These film-forming

materials result in lower water vapor permeability of the surface, causing deterioration to occur below.

The assessment phase has important implications for the development of treatment for areas of unstable painted plaster and for the prevention of further detrimental change to the wall paintings.

Testing and Development

Research and testing were undertaken to develop treatment strategies based on an understanding of the causes and mechanisms of deterioration. The conservation plan was a detailed program for implementation of the strategies, and it describes the activities required, their sequence, duration, and needs in terms of human and material resources.

Conservation strategies in this phase included the following:

- Testing and development of preventive measures to mitigate the causes of deterioration by reducing the intrusion of exterior humid air into the cave and, through limited treatment, to reduce salt content in the earthen plaster in certain areas (see Maekawa et al. and Rickerby et al., “Development and Testing,” this volume).
- Establishment of treatment principles, development of remedial treatment to stabilize the paintings through research on treatment materials and methods, design of testing protocols, and evaluation of results. Treatment developed included a grout mixture for the stabilization of detached plaster through injection grouting (see Rickerby et al., “Implementation,” this volume), a gelatin adhesive to fix flaking paint that was selected on the basis of the identification of protein as the binding medium (fig. 6), and an earthen-based plaster to stabilize edges of the wall paintings.

Measures to Mitigate the Causes and Activation of Deterioration

Removal of the principal cause of deterioration, soluble salts, would be the best way to prevent further deterioration. However, desalination of porous materials is rarely a successful operation (Cather 2003). In addition, the fragile condition of the earthen plasters, their sensitivity to water, and the water-soluble nature of the original protein binder made this option impractical. A management decision was made instead to control relative humidity by keeping the

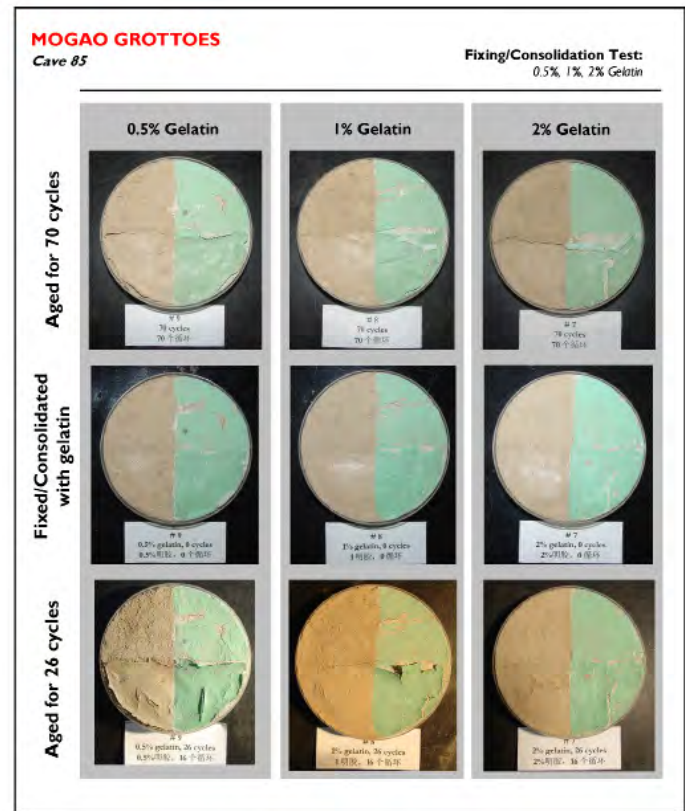


FIGURE 6 Painted plaster disks (loaded with 2% NaCl by wet weight and previously artificially aged for 70 relative humidity cycles [48 hr/100% and 24 hr/ambient RH]) were fixed and consolidated using different amounts of gelatin in water (0.5%, 1%, and 2%). These disks were again cycled to evaluate the performance.

cave doors closed and better sealed during periods of high humidity and rain (fig. 7). This form of passive conservation climate control has been successfully applied to historic buildings (Bläuer Böhm et al. 2001).

Painting Stabilization

Development of interventions to stabilize the deteriorated wall paintings followed the principles of minimal intervention, compatibility, and retreatability and was based on an understanding of the causes and mechanisms of deterioration. Because of the presence of soluble salts in the painted plaster, it was necessary to develop treatments capable of functioning under conditions of high salt content and potential fluctuations in relative humidity. The research, development, and testing of materials with the appropriate properties took several years.



FIGURE 7 Exterior of cave 85 with door closed. A management decision was made to control relative humidity by keeping the cave closed during periods of rain when ambient relative humidity can rise to 75 to 80 percent.

Three main stabilization treatments were developed, as follows:

- Grouting: reattachment of plaster to the conglomerate using a fluid, earth-based mixture with adhesive and bulking properties (see Rickerby et al., “Development and Testing,” this volume).
- Plaster repairs: filling in of lacunae and reinforcement of exposed wall painting edges.
- Fixing and consolidation: reattachment of flaking paint and consolidation of powdering and disrupted conditions associated with exfoliation.

Treatment development and testing started by setting performance criteria and working properties. Performance characteristics relate to the long-term behavior of the materials and measure how the material will function over time; working properties relate to short-term behavior of the material as it is applied and measure its practical ease of use.

To ensure maximum compatibility with the original materials, the clay and silt from the Daquan riverbed were selected as the main binder for the mixture used for plaster fills and grouting. This earth is the same as that used in the original paintings, as confirmed by characterization and particle size distribution of both material from the riverbed and the earthen plaster.² For fixing and consolidation of flakes, pure gelatin in 1 to 2 percent aqueous solution was used.

Implementation

The implementation phase entailed the execution of the conservation strategies, in particular, preventive measures to reduce intrusion of exterior humid air into the cave and remedial interventions to stabilize the paintings and locally reduce soluble salt content. Prior to application on-site, testing and results from treatment development were submitted to an expert committee for approval, a procedure required in China before conservation work can begin on cultural heritage sites of the significance of Mogao.

As part of treatment planning, it was necessary to consider the soluble salts in the plaster that would inevitably be dissolved by the water used in grouting, fixing, and consolidation. Different absorbent materials were tested for use in presses applied after treatment to absorb water and soluble salts and to prevent salt crystallization on the surface of the paintings (see Rickerby et al., “Implementation,” this volume).

Monitoring and Maintenance

A monitoring and maintenance program is necessary to ensure the long-term preservation of the cave after stabilization. Monitoring and maintenance were developed on the basis of the information collected during the project’s diagnostic investigations. The completion of the wall painting conservation program in cave 85 will be followed by regular monitoring and inspection of the condition of the paintings.

The long-term monitoring program is based on post-treatment photographic documentation. Through the conservation project, we were able to identify fourteen representative areas to be monitored, which involves regular inspection to detect any change in condition. DA staff have been trained, and the monitoring areas have been recorded with high-resolution digital photography.

Conclusion

Cave 85 is representative of the remarkable artistic and historic heritage at the Mogao Grottoes and of the site's complex preservation problems. A structured interdisciplinary approach, following the methodology of the China Principles, has been effective in addressing the conservation challenges. Significant steps have been made toward an understanding of the deterioration causes and mechanisms affecting the cave through the collaborative work of the multidisciplinary team. This understanding and the treatment methodology developed have application to other caves at the Mogao Grottoes and at similar Silk Road sites.

This paper presents an outline of the project. Comprehensive details on the analytical and environmental investigations and on testing (flake fixing, grout development, etc.) are available in electronic form in the Cave 85 Project Report of the Getty Conservation Institute and the Dunhuang Academy. Other aspects of the project still in development include recommendations for lighting (see also Druzik, this volume) and a plan for the presentation and interpretation of the cave. Another aspect relates to ongoing research on organic colorants detected on the wall paintings (see Grzywacz et al., this volume).

Acknowledgments

The cave 85 conservation project has been carried out by a multidisciplinary team from the Dunhuang Academy and the Getty Conservation Institute. The authors would like to acknowledge their contribution. Special thanks are due to Neville Agnew and Wang Xudong for direction of the project and refinement of the concepts expressed in this paper. Martha Demas provided guidance and helpful discussion throughout the project.

Notes

- 1 These guidelines are provided online on the Getty Web site: www.getty.edu/conservation/publications/pdf_publications/china_prin_2english.pdf.
- 2 The earthen plaster in cave 85 was made by mixing sand and fibers with the earth from the riverbed.

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The Role of In Situ Examination in the Technical Investigation of the Cave 85 Paintings

Lisa Shekede, Fan Zaixuan, Francesca Piqué, and Lorinda Wong

Abstract: *The late Tang paintings of cave 85 represent a high point of artistic and technical achievement at Mogao. From the outset of the joint Dunhuang Academy–Getty Conservation Institute conservation project, it was clear that the paintings’ technical complexity demanded a thorough investigation, including scientific analysis, archival research, and detailed in situ examination. The scope of the analytical work was wide-ranging and included earthen plaster components, mineral pigments and their alteration products, organic colorants, and binding media. Analytical techniques ranged from light microscopy to gas chromatography–mass spectrometry. Literature research also contributed important contextual information. This paper focuses on the in situ examination of the paintings, defining the relevance of this crucial but often underestimated aspect of technical study. In situ examination has proved crucial in decision making at every step of the conservation process. It therefore deserves recognition, alongside scientific analysis and archival research, as an essential tool of technical investigation.*

Visual examination plays a primary role in the understanding of painting technology, facilitating the accumulation of an unparalleled range of information with the minimum of specialist equipment. Insights gained through careful and systematic visual examination provide a framework for focused analysis and further research, a role that becomes increasingly important with the complexity of the paintings and their deterioration phenomena. This paper examines the key role of visual examination—using normal and raking light, magnification, and multispectral techniques—as the first source of information for all aspects of cave 85

painting technology and explores these findings in the context of complementary resources such as technical literature and analysis.

Plaster and Molded Earth Applications

All aspects of painting technology were executed by the Tang artists with meticulous precision, including the preparation of the painting support. Two layers of earth plaster were applied to the conglomerate rock walls from which the cave was excavated, each with its own function and characteristics. The first is a leveling layer, its thickness varying (5–30 mm) according to the topography of the walls, composed of earth with characteristics very close to those of the alluvial deposits of the local Daquan River.¹ Sand and coarse vegetable fibers (possibly wheat straw) (Duan Xiuye et al. 1993: 307; Yu 1988: 29) were added to improve its properties. The upper plaster layer is likely to be from the same earthen source and appears to have slightly more added sand. Much finer plant fibers, possibly of beaten hemp, were also added, (Duan Xiuye et al. 1993: 307; Whitfield 1999: 210; Yu Feian et al. 1988: 29). These modifications allowed thinner application (1–3 mm) and a smoother finish.

Examination of the plaster joins in raking light indicates that the walls were plastered first, apparently in a clockwise direction, as a distinct vertical overlap can be seen, for example, where the plaster from the south wall overlaps onto that of the east in the southeast corner. The slopes were plastered next, with a considerable overlap of 30 to 40 centimeters extending down onto the walls. Following plastering, dried, molded blocks of earth plaster were applied to provide three-dimensional embellishments. These could be very

simple, such as the rectangular molded blocks at the west end of the corridor entrance, or more complex, such as the molded lotus petal blocks decorating the sculpture platform. With the plasterers' work completed, that of the painting workshop could begin.

Workshop Structure and Practice

It is clear from variations in painting quality and style that a number of different hands were at work in cave 85, with many of the important elements of the scheme executed with skill and precision and others displaying rough-and-ready application. There is also some evidence that colors—at least those forming the basic paint palette—were applied sequentially, probably by divided labor. These features almost certainly reflect a strict workshop hierarchy, for which there is also substantial documentary evidence. Lists of *jiangren* (artisans) and a *huashi* (painting master) in a Tang dynasty document from Turfan indicate the existence of individual painting workshops and testify to their hierarchical working structures, in which up to seven ranks of personnel may have been employed in the execution of a commission (Fraser 2004: 31–34).

Ground Application

The first undertaking of the painting workshop was the application of the ground.² In cave 85 this is a smooth white layer (100–300 μm) composed of calcite, mica, and talc in an animal glue binder.³ Multiple layers of a pink-tinted wash appear to have been applied over this, probably of composition similar to the ground, with the addition of a red organic colorant. Its color survives best in the eastern part of the cave, gradually diminishing toward the west, a pattern indicative of photo-deterioration.⁴ The setting out of the painting commenced after these preparatory layers had been applied.

Conceptualization and Design Transfer

The symmetry of the compositional framework and the complexity of its individual elements are evidence both of a highly evolved preliminary design and of a sophisticated transfer system. A number of preparatory drawings dating to the ninth and tenth centuries preserved among the Library Cave documents provide unique insights into this process.⁵ These rough working drawings, some containing technical and logistical instructions, range from schematic large-scale

designs for entire portions of wall decoration to detailed studies of individual scenes (Fraser 2004: 49).

To transfer these rough sketches, the walls would first have been measured and divided up to accommodate them. Although signs of this have not been found, there is substantial evidence for the setting out of smaller-scale compositional details. Direct, straight-edge incisions—characterized by thin, sharp lines—were used to delineate the spacing of the “beaded pearl” design of the ceiling caisson, to set out text cartouche outlines, and to form guidelines for the texts themselves. Compass incisions were used for setting out haloes, mandorlas, and the beaded pearl decoration on the ceiling (fig. 1).

Cartoons are known to have been used for design transfer during the Tang dynasty, and a number of paper pouncing cartoons from the period survive from the Library Cave cache (Fraser 2004: 49). In cave 85 possible traces of indirect incisions on one of the principal figure compositions—characterized by wide, shallow lines—are too partial and indistinct to constitute firm evidence for cartoon use. It is also clear, from measurements taken of repeat motifs in foliate borders, that cartoons were not used here either. Despite this, the more extended use of cartoons cannot be ruled out, as evidence of pounces, like most of the other preparatory evidence, may simply have been covered over by successive paint layers.



FIGURE 1 Fine straight-edge incisions in the ground layer provide guides for the painted design on the ceiling caisson. Photo: Rickerby/Shekede 2004

Preliminary Drawing

Although evidence for preliminary drawing has largely been obliterated by subsequent paint applications, very dilute black brushwork can still be seen in areas where the painting was accidentally left incomplete. It is probable that most elements of the composition were similarly delineated.

Paint Preparation and Application

The palette of cave 85 is extremely rich, and the diversity of effect is enhanced by skillful paint preparation and application techniques. Over the centuries the deleterious effects of light, humidity, and salts have resulted in color fading, alteration, and paint loss, and although the scheme now appears dominated by green, white, and dark red, careful visual examination of the less deteriorated areas shows that colors susceptible to change—including bright blues, reds, purples, and yellows—were originally important chromatic elements of the painting (figs. 2, 3).

Analysis undertaken during the project has identified a number of paint materials derived from naturally occurring mineral deposits including calcite, mica, talc, orpiment, atacamite, azurite, and iron oxide red. Pigments obtained through chemical and other processes include carbon black, lead white, red lead, and vermilion.⁶ Gold foil was used in cave 85 but very sparingly, being reserved for remarkably small details in the center of the ceiling caisson and on the Sakyamuni statue base. There is also extensive evidence for the use of a range of organic colorants in cave 85 (see below).

Colors were applied in organic binding media.⁷ It is evident from the extraordinary thinness of most paint layers—even those containing very coarsely ground particles—that the medium-to-pigment ratio is high. While this enabled mineral pigments to be applied as semitranslucent glazes, it also made paint susceptible to runs, much evidence for which can be seen in cave 85. Impasto execution is restricted to fine details such as jeweled headdresses, halo patterning, and harness studding.



FIGURES 2 AND 3 Pigment alteration and degradation of organic components is far more severe to the west and north of the cave, clearly demonstrated by comparing a scene on the north wall (left) with a similar scene on the less affected south wall (right). Photos: Rickerby/Shekede 2004

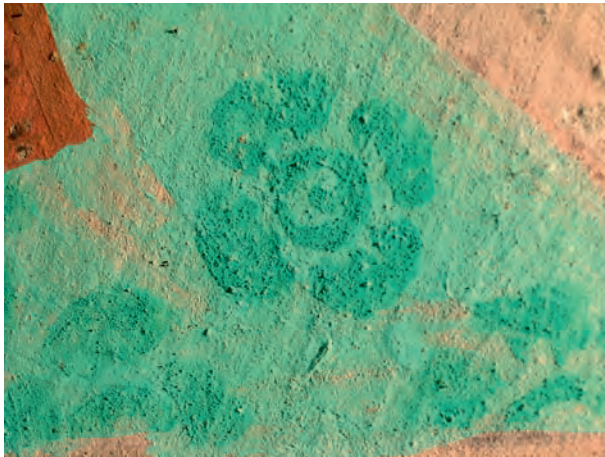


FIGURE 4 A coarse grade of atacamite green superimposed on a finer grade in the depiction of brocade. Photo: Rickerby/Shekede 2004

Examination of areas of the painting where upper layers have been lost provides information on the color range and sequencing of primary paint applications. A narrow range of preliminary colors—chiefly a dull red (red iron oxide), pale green (atacamite), and black (carbon black)—were blocked in first, probably by the lower ranks of the workshop hierarchy (Fraser 2004: 34) (fig. 2). A much broader palette was used for the subsequent layers, from which an incredible variety of effects were obtained (fig. 3). Pigments were used singly or in combination, as washes or in impasto, ground to different particle sizes, combined with organic colorants, and modulated by organic glazes, all following a standardized procedure.

The technique of blending colors on the wall without the use of outlines, sometimes referred to as the “boneless method” (Yu Feian et al. 1988: 52), was used for representing features of diffused color and indistinct form. Extremely sophisticated effects are achieved in cave 85 by superimposing multiple thin, translucent washes of color. Tang dynasty artists exploited this technique to evoke poetic mountain scenery in the so-called blue-and-green (*qinglü shanshui*) style of landscape painting (Zhuang Jiayi and Nie Chongzheng 2000: 42–47), a very accomplished example of which can be seen on the Jataka of Prince Sudana and the Tigers scene on the east wall.

One of the subtlest and most inventive uses of color is achieved by exploiting variations in the optical properties of certain minerals when they are ground to different sizes.

Paint layers composed of coarser particles are thicker, darker, and more intense, whereas those composed of finer particles are thinner, lighter, and more translucent. In cave 85 up to three different grindings of atacamite, azurite, and vermilion can be discerned by color intensity and, in raking light, by the texture of the paint layers. For example, in the depiction of brocade fabrics, a thin wash of finely ground pigment (either azurite or atacamite) is applied as the background color, and then the pattern is picked out in a sparkling, richly colored impasto composed of large particles of the same pigment (fig. 4). The light, delicate greens of tree bark, branches, and leaves, especially the pale gray-greens of willow, are vividly realized by layering the most finely ground grades of atacamite. This practice has a long history in China, having been observed on Qin dynasty wall paintings in Shaanxi province (Liu Qingzhu 1980: 98–99).

Colored Organic Glazes

A wide range of organic colorants are known to have been available to Tang dynasty artists, but until relatively recently their use has been associated almost exclusively with painting on paper and silk, and investigations into their use in Mogao wall paintings have been omitted from almost all technical studies. This is due in part to their limited survival in this context (organic glazes are susceptible to numerous agents of deterioration, most notably light) and in part to the fact that the analytical identification of organic colorants, especially when aged and highly deteriorated, is notoriously problematic. Careful observation reveals, however, that their use was extensive in cave 85. (See also Grzywacz et al., on Asian organic colorants, this volume.)

Traces of colored organic glazes are virtually absent at the western end of the cave, whereas at the eastern end—which has suffered less from salts-related deterioration and light exposure—the original scheme is much better preserved. The most evident organic colorant is a rich, dark purplish red (fig. 5). A variety of effects were achieved by glazing over different opaque layers: over white, it produces a vivid light plum color; over black, a deep, rich, wine red results; mixed with yellow and applied over black, it gives an orange-red; applied over vermilion, it produces a deep, rich pink. The intent behind other applications is much less readily interpreted. For example, an organic red applied to modulate flesh tones is visible only as saturated, darkened patches on cheeks, necks, fingers, and abdomens, in some places so deteriorated that it can be seen only



FIGURE 5 The rich purple-red organic glaze on a decorated halo survives at the east end of the south wall, but few traces have survived toward the west end of the cave due to light exposure and other environmental factors. Photo: Rickerby/Shekede 2004

in UV-induced fluorescence (figs. 6, 7).⁸ Problems in the detection and analysis of many of these fragile materials ensure that their nature and purpose will continue to remain elusive.

There is considerable literary evidence for the use of organic colorants in Tang dynasty painting. The contemporary writer Zhang Yanyuan refers to the use of “ant ore,” which is almost certainly the red organic colorant lac (*Coccus lacca*; Pinyin, *chong jiao*). This was produced beyond China’s southwestern borders and is known to have been imported into the country from an early date (Yu Feian et al. 1988: 12). Safflower (*Carthamus tinctorius*; Pinyin, *honghua/honglanhua*), also widely used, produced an orange-red colorant when treated with an alkali (Gettens and Stout 1966: 154). Library Cave documents attest to its use at Mogao: they record donors offering “honglan” for decorating the caves (Wang Jinyu, pers. com.). Madder (*Rubia tinctorum/R. cordifolia*; Pinyin, *qian cao*) grew wild across northwestern China, from which a rich pink dye was extracted (Yu Feian et al. 1988: 11). These three plant dyes were the most commonly used components in the preparation of “rouge,” which was used both as a cosmetic and as a painting material (Yu Feian et al. 1988: 12). Such com-



FIGURES 6 AND 7 The rosy flesh tones of these chubby boy acrobats, no longer visible in normal light (left), seem to have been achieved using organic glazes, but these can now be seen only in UV-induced fluorescence (right). Photos: GCI 2004

pounds are known to have been available at Mogao, through the presentation of “eight jins of good quality rouge” by a Dunhuang military commander to a local Uyghur chief, documented in Library Cave manuscripts (Wang Jinyu, pers. com). In addition to its use as a color modulator, the application of rouge over vermilion probably had the advantage of lessening the incidence of color change in the latter (Ippolito 1985: 97). Purple colorants were produced from logwood, also called sappanwood (*Caesalpinia sappan*; Pinyin, *su mu*) (Li Ch’iao Ping 1948: 141; Yun Ye, Salmon, and Cass 2000: 248; Yu Feian et al. 1988: 13), and gromwell (*Lithospermum erythrorhizon*; Pinyin, *zi cao*) (Yun Ye, Salmon, and Cass 2000: 246).

Traces of at least two different yellow organic colorants can be observed in cave 85: a dark, rich, glossy yellow-brown, used mainly in the depiction of clouds, and a much paler, dull yellow, traces of which have been detected in architectural detailing, such as counterchanged brickwork and roof tiling. Both may be considerably altered from their original appearance, and it is likely that organic yellows were much more widely used in the cave than is now apparent. Certainly their conspicuous near-absence from the cave contrasts strongly with their abundant presence in Tang paintings on silk and paper.

Numerous yellow dyes were available to Tang dynasty artists. Safflower, described above, produced not only a red dye but also a golden yellow when prepared on an alum mordant (Yu Feian et al. 1988: 11). One of the yellow colorants on the Tang dynasty Diamond Sutra has been identified as amur corkwood (*Phellodendron amurense*; Pinyin, *huang bai*), a bright yellow bark extract originating in Sichuan province (Bell et al. 2000: 234). Rattan, also called gamboge (*Garcinia hamburyi*/*G. morella*; Pinyin, *teng huang*), a colorant indigenous to India, Sri Lanka, and Thailand, was known to have been imported to China before the Tang dynasty (Gettens and Stout 1966: 114–15; Feian Yu et al. 1988: 13). The pagoda tree (*Sophora japonica*; Pinyin, *huai hua*), known to have been in cultivation by the fifth century, yielded a yellow dye that was used with malachite for the specific purpose of improving its adhesion (Ippolito 1985: 89–90; Li Ch’iao Ping 1948: 141). According to the Yuan dynasty author Li Kan, two separate decoctions were prepared from its buds and the petals and used to add luster to different grindings of the pigment. Other available organic yellows include gardenia seed extracts (*Gardenia jasminoides* Ellis; Pinyin, *zhizi*) (Yu Feian et al. 1988: 14; Yun Ye, Salmon, and Cass 2000: 246).

Selective Organic Coatings

Some organic coatings appear to have been applied not primarily to modulate the color of underlying opaque layers but to fix and enrich them. In cave 85 a saturated halo can often be seen around the perimeters of forms painted in atacamite green, which often appear blurred and indistinct. The juice of sticky pearlwort (*Sagina maxima*; Pinyin, *shu yang quan*) was recorded by a Tang dynasty author as being applied over pigments, particularly greens, in order to enrich them and improve adhesion (Yu Feian et al. 1988: 19), and it is possible that extracts of sticky pearlwort—possibly of pagoda tree derivatives (see above)—were mixed with or applied over atacamite green paint layers in cave 85.

Preferential coatings are also visible on some red text cartouches, from which gas chromatography–mass spectrometry (GC-MS) analysis has identified fruit gum. These have a saturated and glossy appearance, and many also have a preferentially exfoliating surface. The purpose of these applications was perhaps to protect, add luster, or improve legibility of scriptures and other texts.

Final Drawing

During the Tang dynasty, the final delineation of objects became an increasingly important stage of the painting’s execution and would have been carried out by the most senior members of the painting workshop (Barnhart 1997: 83–85). Extremely refined and economical drawing can be observed in cave 85. Both black and red were used for this purpose and would have been applied using the same bamboo- and animal-hair brushes as those used by calligraphers, whose mastery of line was equally prized (Zhuang Jiayai and Nie Chongzheng 2000: 16–17) (fig. 8).

Conclusion

The investigation of wall painting technology is always restricted by the limitations of available resources. For cave 85, despite the investigative resources of a long-term, multidisciplinary conservation program, the complexity of both the paintings and their deterioration remains a formidable obstacle to their complete understanding. Important aspects of technique and condition elude both analytical detection and interpretation, and their significance is not always recognized. Degraded organic components continue to challenge the detection limits of currently available



FIGURE 8 Sinuous and highly controlled line drawing from an especially fine figure group on the south wall. Photo: Rickerby/Shekede 2004

analytical methods. Although contemporary documents offer fascinating glimpses of workshop practice and the use of materials, they remain silent on many of these issues. With these limitations in mind, this paper has demonstrated the versatility of in situ visual examination as a means of exploring aspects of painting technology—from the broadest patterns to the most minute phenomena—that cannot be done by any other means.

Notes

- 1 For the results and discussion of earthen analysis, see Rickerby et al., “Development and Testing,” this volume.
- 2 This may have been preceded by the application of a glue and alum sealant, a practice referred to in the literature (Lu Hongnian 1956: 15–17; Feian Yu et al. 1988: 18). Although there is no visual or analytical evidence for this, its use over the ground and subsequent layers is suggested by GC-MS and SEM analysis (Schilling et al., this volume).
- 3 The results of paint analysis are discussed in Schilling et al., this volume.

- 4 Although light levels in the cave are currently low, the historic shearing of the cliff face and loss of the front chamber left the paintings exposed for a prolonged period, until the current facade was built in 1963–64. In any case, the severity of photo-deterioration is determined not only by light intensity but also by exposure time (Gowing 2003: 91–92).
- 5 Cave 17, known as the Library Cave due to the enormous number of documents found there, was rediscovered in 1900 after having been sealed in the eleventh century. For further information, see Whitfield, Whitfield, and Agnew 2000: 121–31.
- 6 See note 3. It is unclear whether naturally occurring cinnabar or the artificially produced pigment, vermilion, was used in cave 85. Either is possible, as cinnabar occurs naturally in southern China, while dry-process vermilion, thought to have been invented in China, was in production at a much earlier date (Gettens, Feller, and Chase 1993: 160–61).
- 7 GC-MS analysis indicates that animal glue was the most extensively used binder, but plant gums and mucilage may have also been used for some applications. See note 3.
- 8 Successful imaging of organic components and underdrawing was undertaken by Lorinda Wong and Francesca Piqué using GCI-supplied MuSIS™ multispectral imaging equipment, operating across 380–1,000 nm.

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Analytical Research in Cave 85

Michael R. Schilling, Joy Mazurek, David Carson, Su Bomin, Fan Yuquan, and Ma Zanfeng

Abstract: *The project to conserve the wall paintings in cave 85 at the Mogao Grottoes presented many analytical challenges that taxed even the most sophisticated laboratory instrumentation. The first, and often overlooked, aspect of the process was a careful in situ examination of the wall paintings by an experienced conservator for the purpose of selecting the samples. Next, the analytical tools for the studies were selected on the basis of versatility and detection limit. Organic binding media were identified using gas chromatography–mass spectrometry and Fourier transform infrared spectrometry. Dispersions of pigment particles were examined by polarized light microscopy. Inorganic pigments were identified using X-ray diffraction, whereas organic pigments were analyzed with liquid chromatography–mass spectrometry and thin-layer chromatography. The reflectance spectra and lightfastness of organic pigments were studied by microfadeometry. Examination of paint cross sections revealed information about the layering and materials; elemental distributions in the paint layers were studied using scanning electron microscopy and energy-dispersive X-ray spectrometry. Water-soluble salts were analyzed by ion chromatography and by ion-selective electrodes. For decisions about the order of application of multiple analytical techniques, the quantity of available sample was the key consideration. Final compilation of the corpus of analytical test results into a database not only was useful for the purposes of archiving and sharing information but also gave the additional benefit of greatly facilitating data interpretation. Implementation of this systematic analytical approach in cave 85 revealed a level of complexity in the wall paintings that was not previously imagined. This paper discusses selective results and findings from each major area of analytical*

investigation and the organizational structure of the project's analytical database.

In the project to conserve the wall paintings in cave 85, material analysis played a critical role in three major project areas: (1) studying the artists' materials and painting technique, (2) seeking to understand the causes of deterioration of the wall paintings, and (3) assessing the content and distribution of hygroscopic salts in the paint, plaster, and conglomerate rock. Analytical research in these project areas involved characterization and identification of a wide variety of materials: inorganic and organic pigments, organic binding media, water-soluble salts, earthen plaster, and plant fibers. To accomplish these objectives, numerous analytical techniques were employed and new sample preparation procedures developed or refined as needed. Except for a few samples sent to outside laboratories for specialized tests, the majority of analyses were carried out in the scientific laboratories of the Dunhuang Academy and the Getty Conservation Institute (GCI).¹ Implementation of this systematic analytical approach in cave 85 revealed a level of complexity in the wall paintings that was not previously known.

Materials and Technique

The rough-hewn conglomerate walls of the grottoes are covered with two layers of earthen plaster: a coarse underlayer and a fine upper layer. Particle size analysis of the earthen material revealed a composition of 36 percent sand, 45 percent silt, and 19 percent clay. The bulk minerals were identified in decreasing order of abundance as quartz, dolomite,

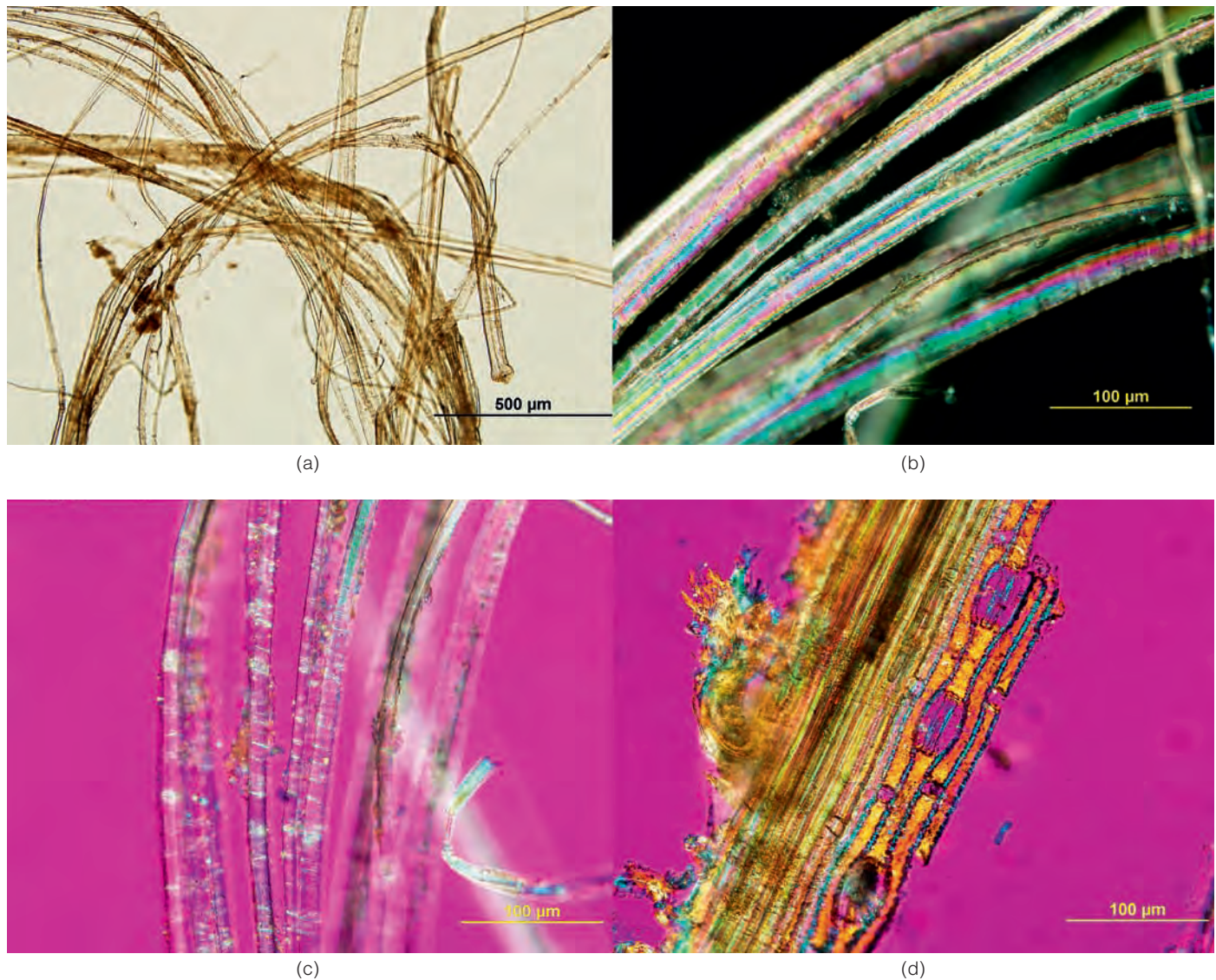


FIGURE 1 Photomicrographs of plant fibers from the upper and lower plaster layers.

calcite, orthoclase feldspar, and plagioclase feldspar. The clay-size fraction consists of 40 percent illite, 30 percent chlorite, and 30 percent mixed-layer illite/smectite (Austin 1998). Sodium chloride, originating from the hygroscopic salt mixture present in the conglomerate, was detected by XRD in a small number of plaster samples with unusually high salt content.

Natural plant fiber bundles from the fine upper plaster layer, shown using a 10 \times lens with single-polar illumination (fig. 1a) and a 40 \times lens using crossed-polar illumination (fig. 1b), are typical of untreated bast fibers. In figure 1c, the fibers are oriented perpendicular to the polarizer with a first-

order compensator inserted, and the faint blue colorization in this orientation is a feature of positive (z-twist) natural fibers, of which there are many. Natural plant fiber fragments from the coarse lower plaster layer appear more like tubular cereal grass (fig. 1d); the edge of one of the pieces shows the serrated cells and what appear to be stomata. Considering the absence of other key morphological features and lacking knowledge of species distribution in China, it was not possible to specify the plant species further (Bisbing 2006).

Analysis of pigments in the wall paintings afforded a few surprises. In general, the mineral pigments identified in cave 85 using PLM, XRD, and ESEM-EDX were consistent

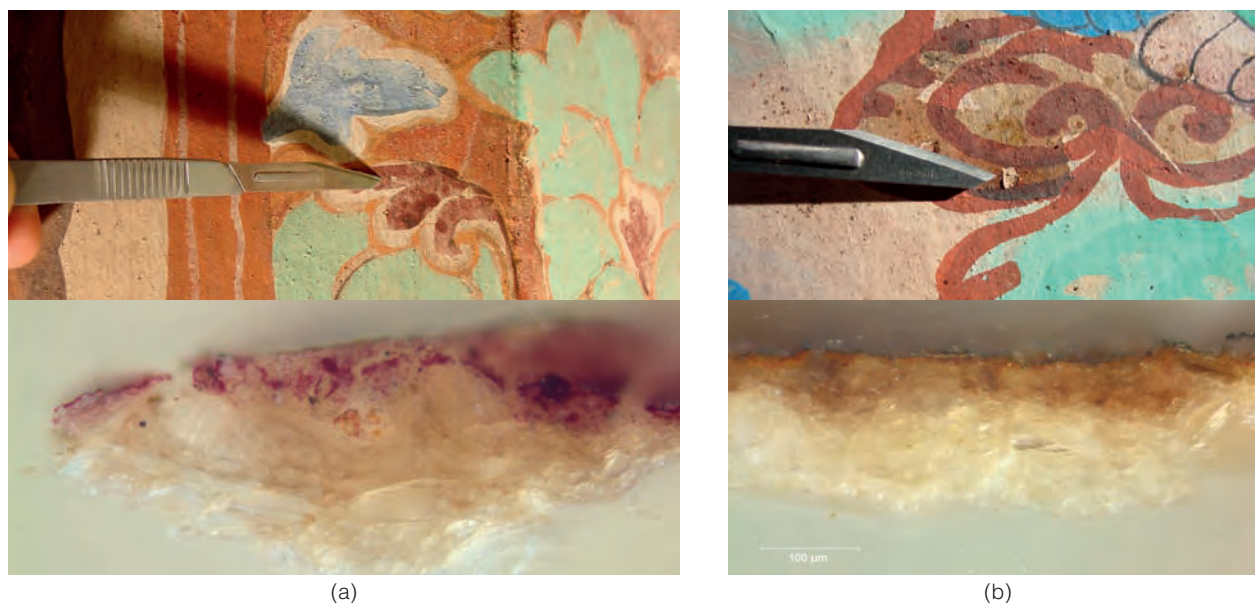


FIGURE 2 (a) Reddish purple color from a decorative border on the east wall with inset darkfield photomicrograph of paint cross section (sample F03S01); (b) translucent brown from cloud on south wall with inset darkfield photomicrograph of paint cross section (sample F03S21).

with numerous technical studies of the Mogao Grottoes wall paintings (Guo Hong 1997; Wainwright et al. 1997; Wang Junhu, Li, and Schilling 1995). To summarize the findings, the fine earthen plaster is covered by a white ground layer from 20 to 200 microns in thickness composed of calcium carbonate, mica, and talc; the ground layer exhibited weak UV fluorescence in paint cross sections. Numerous inorganic pigments were detected in the wall paintings, such as azurite, malachite, atacamite, red lead, cinnabar, red iron oxide, yellow ocher, white lead, orpiment, and carbon black. Black lead, or plattnerite, was also identified as a product from transformation of red lead and white lead pigments. Overall, paint layers ranged in thickness from 5 to 100 microns.

The conservation team noted a number of shades of color on the wall paintings that could not have been produced from admixtures of the common Tang dynasty mineral pigments. Readily observed on the slopes, upper walls, and ceiling panel in locations that are shaded from direct sunlight exposure via the opening to the cave, many of these colors fluoresced strongly under UV light. One example is a reddish purple color from a decorative border around the walls and slopes (fig. 2a). In a cross section from this area, the paint appears as minute red particles smeared onto the white ground. ESEM-EDX analysis of this cross section shows an absence of elements associated with typical red mineral pigments (e.g., iron, mercury, or lead) and instead a slight

enrichment in aluminum and potassium. These elements are consistent with the use of alum for precipitating dyestuffs in the manufacture of organic pigments and also with the application of a preparative glue sizing layer (Yu Feian, Silbergeld, and McNair 1988; Shekede et al., this volume).

Given the widespread usage of organic colorants in cave 85 and in other caves, it is surprising that few publications mention the use of these important artists' materials in the context of Mogao (Xu Weiye, Zhou Guoxin, and Li Yunhe 1983). One contributing factor is that conventional techniques that work so well for identifying mineral pigments are incapable of detecting organic materials of any sort. Detection and identification of traditional Chinese organic colorants present an additional challenge not only because many of the biological sources used to create them have not been well studied but also because in the case of organic paints concentrations of these colorants are low compared with those of inorganic pigments and binding media. Much less is known of these colorants than of the dye and organic pigment sources used in Europe and the Americas. Moreover, organic pigments can become unrecognizable due to fading or darkening in the more easily accessible areas of the wall paintings. Thus even if suitable organic pigment standards were available, the analytical results for fresh and aged pigments might differ substantially. To address these issues, research is currently under

way to investigate the identification of organic colorants in Asian wall paintings (see Grzywacz et al., this volume).

Identification of the organic binding media proved more complex than anticipated, due to the presence of organic colorants in many of the paint samples. With FTIR, no paint media were detected in paint and ground samples above the instrumental detection limit of 5 to 10 percent by weight. However, many spectra showed characteristic infrared (IR) bands for oxalates. These include intense bands at $1,622\text{ cm}^{-1}$ and $1,320\text{ cm}^{-1}$, plus medium-intensity bands at 780 cm^{-1} and 668 cm^{-1} , for the dipole moment of the carboxylate group stretching. Bands at $1,622\text{ cm}^{-1}$ and $1,320\text{ cm}^{-1}$ are due to the asymmetrical and symmetrical carboxylate group stretching, respectively. Oxalates are formed from chemical and microbial conversion of organic materials but are also commonly present in the tissues of plants that thrive in arid climates (Wainwright et al. 1997).

An earlier study of binding media in the wall paintings of Mogao, using liquid chromatography to analyze amino acids in acid hydrolysates of 2-milligram paint samples, clearly demonstrated that collagen-based proteinaceous materials such as animal glue were used in the majority of the caves surveyed. In contrast, the amino acid compositions of the remainder of the samples correlated somewhat broadly to fruit gums; in these polysaccharide-based materials, amino acids are present in the form of glycosides (Li Shi 1995), although no mention was made of the existence of organic colorants in the paintings.

To identify the binding media in cave 85, paint samples (in the submilligram range) were prepared for quantitative GC-MS following protocols developed for identification of protein and polysaccharide binding media in easel paintings (Schilling 2005). Both procedures involve an acid hydrolysis step to depolymerize the media, followed by chemical derivatization to produce volatile analytes suitable for GC. Proteinaceous binding media were identified on the basis of amino acid composition (Schilling and Khanjian 1996a, 1996b), and plant gums on the basis of carbohydrate composition (Schilling 2005). Compositional data were evaluated using correlation coefficients and principal component analysis, which are two common statistical evaluation tools (Columbini et al. 1998; Schilling and Khanjian 1996b). Of the twenty-six samples tested for carbohydrates, only fourteen were analyzed for amino acids due to limits on sample quantity. Table 1 lists the results from the quantitative GC-MS analysis of amino acids and carbohydrates.

For eleven samples, the amino acid composition matched collagen unambiguously, with a correlation coef-

ficient exceeding 0.8 for each sample. The amino acid composition of two samples (NQ01PE11 and YDNQ01PE14) correlated more closely with that of a white residue that was formed by microbial activity between the conglomerate and the earthen plaster. The residue was initially thought to be hygroscopic salt, but microscopic examination instead revealed a mass of microbial hyphae. The binding medium in only one sample (BP00PE9) could not be identified because the amino acid content was, essentially, at the experimental detection limit of 0.1 weight percent. It is clear from these data that a collagen-based material such as bone glue or hide glue was the principal binding medium used in cave 85.

In studies of Western easel paintings, it is often relatively easy to identify plant gum binding media because only a few gums were in common usage (gum arabic, gum tragacanth, and prunus gum). Concerning the GC-MS tests for carbohydrates in cave 85, eighteen of the samples tested had total carbohydrate contents exceeding 0.1 percent by weight, but the compositions proved unusually variable. Many of the samples contained glucose and fructose, with smaller amounts of other carbohydrates typically present in plant gums and mucilages. Fructose and glucose, two sugars that are not common in fruit gums, may originate from several sources. Fructose is relatively abundant in honey, but it is also present in plant mucilages such as in *Eremurus* root, which has been reported in a study of central Asian art (Birstein 1975). Plant fibers added to the plaster contribute carbohydrates, primarily glucose but also xylose, on chemical degradation. Therefore, if one ignores the content of fructose and glucose in the samples and interprets the data for the remaining carbohydrates, a few of the paints correlated closely with apricot gum (sample DP98PE12), gum tragacanth (NQF03S24), and even gum arabic (PLATXQ98P2). In each of these samples, however, the concentration of fucose and/or mannose did not match with these plant gums at all, thus making the identification of gums in the paints somewhat suspect.

Interpretation of the carbohydrate data for the cave 85 paint samples was further complicated by several factors. First, organic colorants naturally contain carbohydrates in the form of glycosides, which contribute to the overall carbohydrate composition of the paint. Moreover, the artists may have applied other carbohydrate-containing materials besides fruit gum, such as plant mucilages. Finally, interferences from mineral pigments and physical aging may affect the carbohydrate composition of the paint media. Considering all these factors when attempting to draw conclusions about the sources of carbohydrates in the cave 85 paint samples, it

Table 1 Summary of GC-MS Quantitative Analysis Results of Paint Samples from Cave 85

Sample	Description	Normalized Mole Percentages										Normalized Weight % of All Carbohydrates									
		Amino Acids	Ala	Val	Ile	Leu	Gly	Pro	Hyp	Sugars	Rham	Fuc	Rib	Arab	Xyl	Mann	Fruct	Glu	Gal		
JXDB00P1	Organic red	5.9	13	5.7	4.0	6.6	61	7.8	1.8	0.77	0.7	0.4	0	5.4	2.2	1.8	69	4.3			
YDNQ01PE14	Gray	2.6	21	12	9.3	18	22	11	6.7	0.76	0.5	0	2.1	64	1.1	0	30	2.4			
NP.F03.S29	Dark red	0.8	14	3.1	2.7	3.5	44	18	15	<0.1											
NQ.F03.S24	Brown-resinous	0.7	16	8.8	7.3	8.2	21	19	20	0.40	1.0	0	41	6	4.0	4	26	10			
DQ00PE16	Red & ground	0.4	17	3.7	2.9	4.9	31	25	16	0.23	0	0	2.5	3.2	0	35	58	0.6			
NQ.F03.S25	White	0.4	20	6.6	4.3	5.7	35	18	11	<0.1											
NP.F03.S22	Pink	0.4	15	3.6	2.7	3.7	41	16	19	<0.1											
NQ.F03.S08	Red	0.4	17	5.9	5.1	6.1	45	12	9.3	<0.1											
JXNB01PE13	Discolored ceiling	0.39	19	3.6	2.0	4.1	48	15	8.6	0.12	1.1	0	2.7	1.6	2.2	16	73	3.2			
DP.F03.S17	Brown	0.3	16	9.6	6.9	10	40	13	4.2	<0.1											
DQ00PE15	Blue & ground	0.22	20	6.1	4.1	7.6	26	18	18	0.10	0.4	0	7.2	7.0	0	22	60	3.3			
NQ01PE11	Colored ground	0.12	24	7.6	5.5	12	38	12	0.0	2.6	0	0	5.4	18	0	0	71	6.2			
BP00PE9	White	0.12	14	7.0	7.5	13	13	28	18	<0.1											
DQ.F03.S20	White	0.1	19	8.9	5.6	10	26	15	16	<0.1											
Collagen	Mean data	84	16	3.0	1.8	3.7	47	17	12.4												
Whole egg	Mean data	46	22	17	13	22	15	11	0.0												
Microbe	Cave 85	13	22	14	16	17	23	7	0.3	16	0	0	0.6	1.2	16	0.2	22	59			
Gum	Iranian Kurdistan	68	3.2	3.7	0	50	13	0	0	0	0	0	0	0	0	0	17	13			
tragacanth																					
Mucilage	Cucumber	52	0.6	0	1	3	2	0.3	36	52	6										
Apricot gum	Mogao	70	1.0	0	0	40	7.0	4.0	0	2.0	46										
Gum arabic	England	59	22	0.1	0	36	0	0	0	0.2	41										
DP98PE12	Shiny brown	8.4	1.5	2.9	0.6	20	9.5	2.4	19	25	19										
PLATXQ98P2	Amber "resin"	4.1	7.3	4.5	2.7	9.7	6.9	4.5	1.5	45	18										
NP98P9	Red	2.2	0	0.1	0	3.3	44	13	3.5	33	2.5										
NQ01PE12	White ground	0.75	0	0	0	21	0	0	0	79	0										
DP98PE13	Tan	0.23	1.2	0	0.6	6.7	3.7	1.8	47	31	7.9										
JXNB98PE11	White & earth	0.23	0	0	0	2.2	2.2	0	32	63	0.7										
NPOOPE4	Red, ground & earth	0.21	0.6	0.5	0	3.6	3.7	2.1	25	59	5.4										
PLATXQ98P2	Red & ground	0.21	16	1.2	1.5	15	7.3	4.7	10	22	22										
XQ98PE2	Red	0.20	3.7	0	0	8.9	16	4.4	21	40	6.7										
NQ98P4	Red & ground	0.17	2.4	0	0	7.2	78	7.2	0	0	4.8										
DQ98PE3	Tan & earth	0.12	0.4	0.1	0	8.2	5.0	0	7.3	75	3.4										

was decided to avoid overinterpreting the test results for the remaining samples and wait until more research is carried out. The results of this study make it abundantly clear that this area is ripe for future exploration.

Discovery of organic colorants in the wall paintings was one of the most surprising findings of the cave 85 project. Their presence in the wall paintings influenced many aspects of the project, including analysis of the artists' materials and painting technique, conservation treatments, and assessing safe levels of illumination. Consequently, a research project has been initiated at the GCI, in collaboration with the Dunhuang Academy, to study organic colorants in Chinese wall paintings (see Grzywacz et al., this volume).

Pigment Alteration

Another interesting aspect of the analytical research was investigating the appearance and condition of the wall paintings, and two examples will illustrate some of the more important results. For instance, a paint cross section from a bluish green robe of a figure on the east slope was studied by light microscopy and ESEM-EDX (figs. 3a, b). The cross section shows greenish particles in the paint layer, many of which have blue centers. Elemental maps of copper and chlorine show a progressive inward transformation of the blue azurite particles to the green pigment atacamite. The conver-

sion of azurite to atacamite has been shown to proceed when environmental conditions are favorable and chloride ion in wall paintings is abundant (Dei et al. 1998; Kerber, Koller, and Mairinger 1972; Naumova and Pisareva 1994).

It was discovered that some colors in cave 85 exhibit a blanched appearance that is related to the transformation of arsenic sulfide pigments. Orpiment, a yellow mineral, As_2S_3 , has been identified in wall paintings at Datong (Piqué 1997) and Mogao (Guo Hong 1997). Orpiment may, under certain circumstances, lose its color to form white arsenic trioxide; exposure to light, ozone, and heat are all known to affect the rate and extent of the reaction (FitzHugh 1997; Walker 1999). This explains why orpiment crystals in mineralogical displays occasionally are covered with a thin, powdery, white layer. Realgar, a red mineral, As_4S_4 , has seldom been identified in Chinese wall paintings. Realgar is also light sensitive and is less permanent than orpiment, transforming into pararealgar, orpiment, or arsenic trioxide (FitzHugh 1997).

In addition to light exposure, microorganisms have the potential to transform arsenic pigments. It is known that microorganisms are capable of altering pigments in wall paintings (Petushkova and Lyalikova 1986) and, moreover, that some microbes are capable of thriving even in the presence of highly toxic arsenic minerals. For instance, several bacteria, including *Pseudomonas arsenitoxidans*, can convert orpiment and realgar to arsenite and arsenate. In aerobic

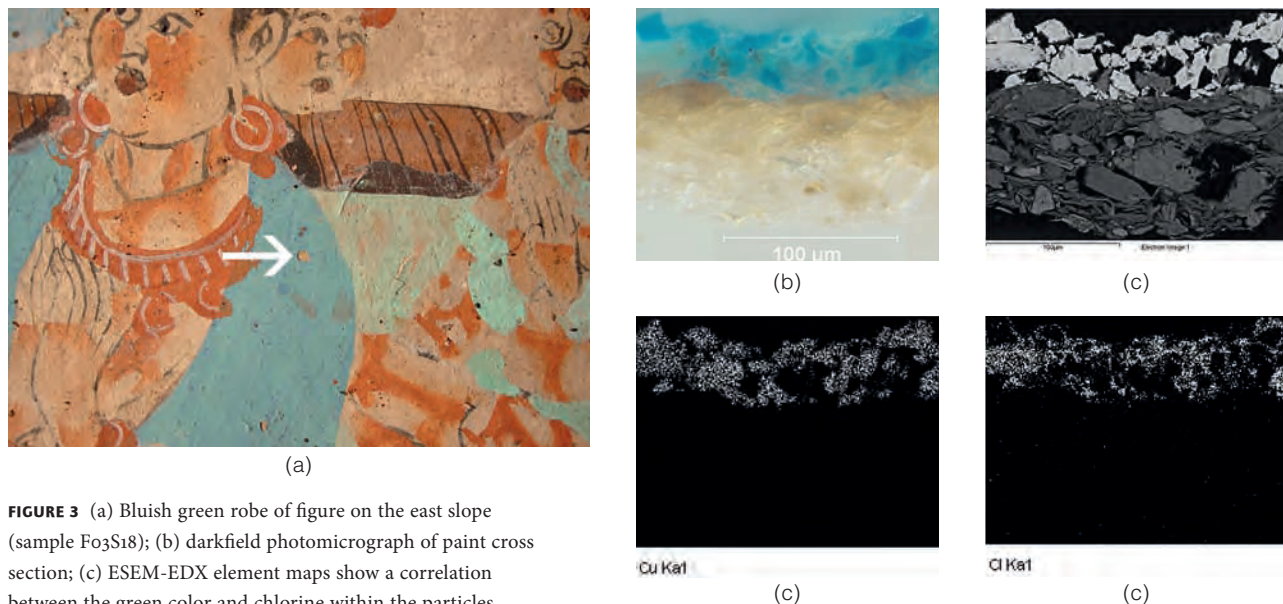


FIGURE 3 (a) Bluish green robe of figure on the east slope (sample Fo3Si8); (b) darkfield photomicrograph of paint cross section; (c) ESEM-EDX element maps show a correlation between the green color and chlorine within the particles, which indicates a progressive inward transformation of blue azurite into green atacamite.



FIGURE 4 Figure on the east wall with a blached flesh tone (sample F03S20); and darkfield photomicrograph of a paint cross section (inset).

conditions, some fungi, such as *Scopulariopsis brevicaulis* and *Penicillium* sp., are capable of biomethylation of arsenic oxyanions to form trimethyl- or dimethylarsine (Kurek 2002). *Scopulariopsis* colonies, which grow moderately rapidly and mature within five days, are granular to powdery in texture; the surface color is white initially, becoming light brown or buff tan over time (Sutton, Fothergill, and Rinaldi 1998).

From the study of the artists' materials in cave 85, unaltered orpiment was identified in only one area: directly beneath a red lead layer from a figure on the east slope (sample 85DP98PE12). The red lead layer on the figure would have protected the orpiment both from light exposure and from microbial activity. More typical was the detection of arsenic in several painted areas that exhibited a blached whitish appearance, such as in the flesh tone of a figure on the east wall (fig. 4). In cross section, white globular clumps on the surface of the painting (inset) were found to be rich in arsenic but lacking in sulfur. Microscopic examination revealed that the surface was covered with white microbial hyphae that stained positively using methylene blue. In none of the blached paints was XRD capable of identifying the white, arsenic-containing substance. GC-MS analyses of these same areas showed a reduced content of binding medium.

Although it should be possible to identify the microorganisms present in the white efflorescence on the blached paints in cave 85 by DNA analysis, the quantity of available material at the time was extremely limited. Instead, the DNA of a much larger white deposit present on several colors of the wall paintings in cave 98 (fig. 5), another large late Tang dynasty cave similar to cave 85, was analyzed using a nested polymerase chain reaction approach. This technique improves the detection of DNA by double amplification using two sets of primers and sequencing the bands of separated DNA. The deposit, albeit difficult to analyze because of age and limited amount of residual DNA, was shown to consist of a mixed, largely unidentified, microbial colony. Interestingly, many of the identifiable bacteria species were found to be capable of oxidizing sulfides, sulfur, and thiosulfates; one such species was *Sulfurimonas* (Mazurek 2007).

To summarize the findings, the example of the blached flesh tone layer provides evidence for transformation of arsenic sulfide pigment into an obscuring whitish tan layer. During this process, arsenic-tolerant microbes may have metabolized the paint media, greatly reducing its concentration. The arsenic sulfide pigment has converted, either by the action of microbes or by exposure to light, into a white compound lacking sulfur. Considering that the compound could not be identified by XRD, this finding lends some support to

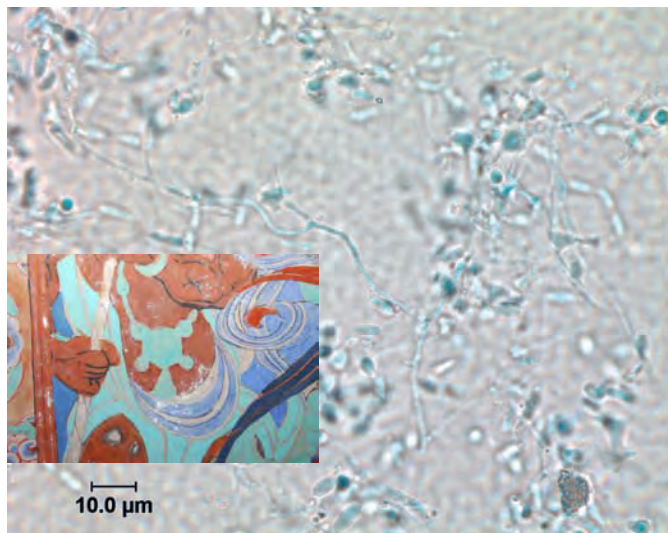


FIGURE 5 Photomicrograph of white microbial deposit (after staining with methylene blue) that is present on the wall paintings in cave 98.

Table 2 Summary of Salt Distribution Data in Cave 85 Based on Microcore Salt Survey

Summary of Ion Chromatography Results for Plaster Microcore Samples								
Sample Location	Anion to Cation Ratio	Meq of Ion (normalized)/100 g Plaster						
		Cl	NO ₃	SO ₄	Na	K	Mg	Ca
Cave 85, eastern end, above 2 m	0.6 ± 0.1	12 ± 8	1.3 ± 0.7	24 ± 9	40 ± 11	2.5 ± 0.6	2.6 ± 1.5	18 ± 8
Cave 85, western end, above 2 m	0.8 ± 0.1	27 ± 6	1.1 ± 0.2	16 ± 4	46 ± 3	1.1 ± 0.3	0.7 ± 0.3	7.3 ± 3.5
Cave 85, eastern end, below 2 m	0.9 ± 0.02	38 ± 4	5.4 ± 2.0	4.3 ± 1.6	17 ± 13	1.0 ± 0.2	16 ± 6	18 ± 6
Cave 85, western end, below 2 m	0.9 ± 0.1	32 ± 3	1.1 ± 0.3	14 ± 1	47 ± 1	0.9 ± 0.2	0.5 ± 0.2	4.3 ± 1.4
Conglomerate from storage area	0.8	23	1.2	19	43	0.3	2.9	10
Cave 61, eastern end	0.8 ± 0.1	16 ± 5	5.8 ± 1.2	21 ± 9	31 ± 12	3.1 ± 0.9	5.8 ± 0.7	17 ± 9
Cave 61, western end	0.8 ± 0.1	18 ± 6	3.1 ± 1.4	22 ± 9	31 ± 8	3.7 ± 2.0	6.6 ± 3.3	16 ± 5
Cave 98, eastern end	0.8 ± 0.2	19 ± 11	1.2 ± 0.5	23 ± 9	36 ± 12	1.9 ± 1.3	3.9 ± 2.9	15 ± 10
Cave 98, western end	0.9 ± 0.1	22 ± 7	1.0 ± 0.7	23 ± 6	35 ± 6	1.2 ± 0.5	2.1 ± 1.3	15 ± 5
Weight Percent of Ion in Plaster								
Sample Location	Weight %	Cl	NO ₃	SO ₄	Na	K	Mg	Ca
Cave 85, eastern end, above 2 m	0.6 ± 0.2	0.1 ± 0.1	0.02 ± 0.01	0.2 ± 0.1	0.2 ± 0.1	0.02 ± 0.004	0.006 ± 0.002	0.07 ± 0.03
Cave 85, western end, above 2 m	2.3 ± 1.0	0.8 ± 0.4	0.05 ± 0.03	0.5 ± 0.2	0.8 ± 0.3	0.03 ± 0.01	0.006 ± 0.003	0.09 ± 0.05
Cave 85, eastern end, below 2 m	2.8 ± 0.4	1.3 ± 0.3	0.32 ± 0.10	0.2 ± 0.1	0.4 ± 0.3	0.04 ± 0.001	0.19 ± 0.08	0.36 ± 0.15
Cave 85, western end, below 2 m	3.5 ± 1.3	1.3 ± 0.6	0.07 ± 0.02	0.8 ± 0.3	1.2 ± 0.4	0.04 ± 0.01	0.006 ± 0.001	0.09 ± 0.03
Cave 61, eastern end	0.9 ± 0.2	0.2 ± 0.01	0.1 ± 0.01	0.3 ± 0.2	0.2 ± 0.03	0.03 ± 0.002	0.02 ± 0.01	0.10 ± 0.08
Cave 61, western end	1.2 ± 1.3	0.2 ± 0.1	0.05 ± 0.01	0.5 ± 0.7	0.2 ± 0.3	0.04 ± 0.01	0.02 ± 0.02	0.12 ± 0.11
Cave 98, eastern end	2.3 ± 2.2	0.7 ± 1.0	0.04 ± 0.02	0.7 ± 0.5	0.6 ± 0.8	0.04 ± 0.01	0.02 ± 0.01	0.16 ± 0.09
Cave 98, western end	2.8 ± 0.8	0.7 ± 0.4	0.05 ± 0.02	1.0 ± 0.4	0.7 ± 0.2	0.04 ± 0.01	0.02 ± 0.01	0.26 ± 0.12

the microbial-induced transformation mechanism because arsenic trioxide is known to form from orpiment by light exposure. The sulfide counter-ion from the arsenic pigment has likely dissipated as hydrogen sulfide, a conclusion that is consistent with either mechanism. Although the microorganism growing on the blanched arsenic-containing paint has yet to be identified and the precise role of light in the transformation process is uncertain, it is clear that microbial activity must be considered in searching for explanations of the blanching phenomenon.

Hygroscopic Salts

Hygroscopic salts have caused great damage to the wall paintings, and therefore much analytical work was conducted in order to study their composition and distribution in the conglomerate rock, plaster layer, and paintings using ion chromatography (IC), ion-selective electrodes, and ESEM-EDX. A summary of IC data for the microcore plaster samples that were obtained from forty-seven sample locations is presented in table 2. The IC method employed for the tests detected most of the common cations and anions

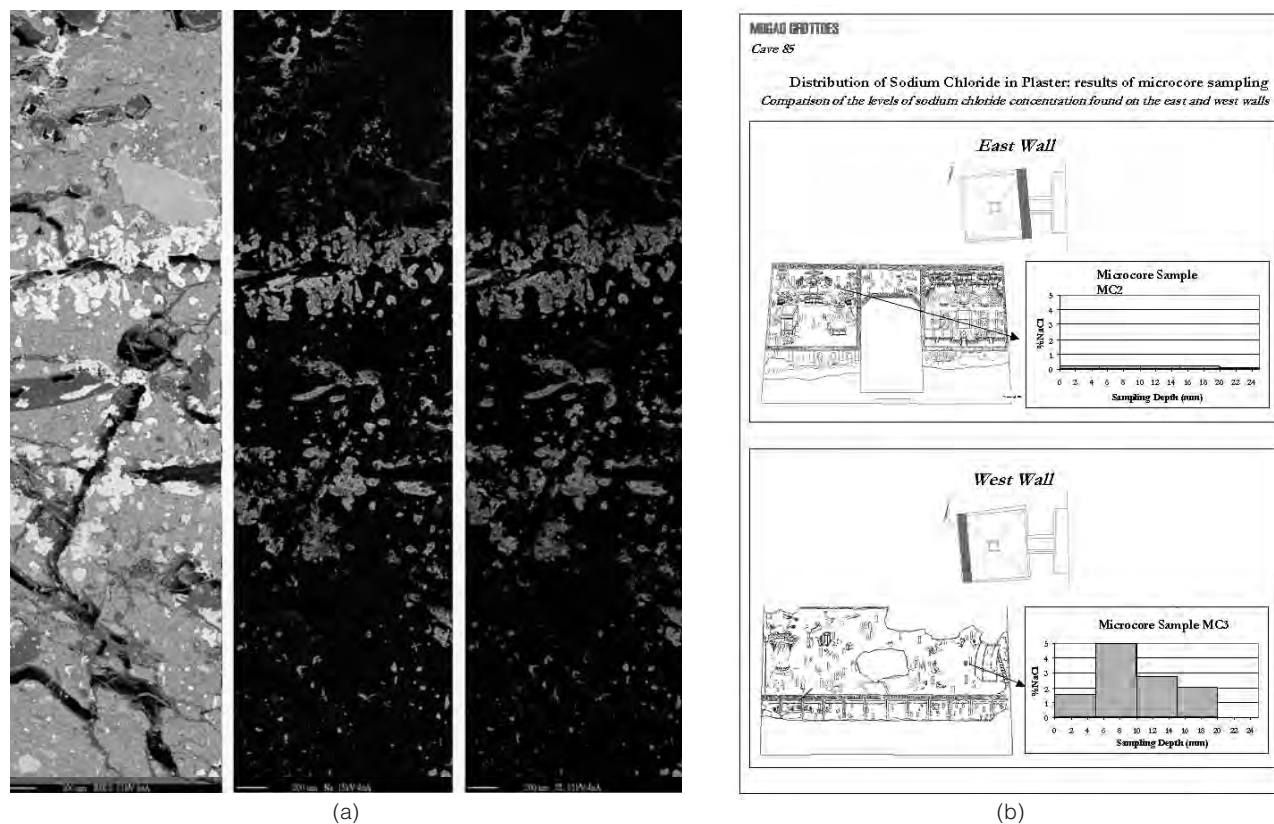


FIGURE 6 (a) ESEM-EDX element maps for a cross section of plaster from the west end of the north wall (sample 85BQ99E3); (b) salt profiles for plaster microcore samples from the east and west walls.

in hygroscopic salt mixtures. However, independent tests of salts in core samples of the conglomerate rock from cave 98 confirmed the presence of small amounts of bicarbonate and carbonate within the conglomerate (Lin 2005). These two anions were not detected by the IC method; hence their absence from the data set in table 2 may partly explain the deficit in the anion to cation ratio for the cave 85 microcore samples.

The pH of the hygroscopic salts may affect the deterioration rate of organic materials such as the paint media and plant fibers, as well as the discoloration of mineral and organic pigments. Sheng Fenling, Li Zuixiong, and Fan Zaixuan (1993) reported a pH of 7.6 for the Daquan River, which is one source of salt in the caves. In a broad study of a core sample of conglomerate rock from cave 98, Lin (2005) reports a pH of 8.64 for the salt extracted from the conglomerate. According to test strips, the mean pH of the cave 85 plaster microcores was approximately 7, although the accuracy of test strip measurements is certainly less than for readings obtained by a pH

electrode. In summary, the salts in and around cave 85 tend to be slightly alkaline.

It is clear from table 2 that salts are substantially enriched in the plaster at the west end of the cave, which is consistent with the greater extent of observed damage there, compared to that at the east end of the cave. This trend is also observed in cave 98, which exhibits the same extent and type of damage as cave 85, whereas in cave 61 the salt content is substantially lower, as is the corresponding degree of damage.

Although many anions and cations are present in the hygroscopic salt mixtures listed in table 2, sodium chloride is by far the predominant damaging salt. Crystalline deposits of nearly pure sodium chloride were discovered on the inner face of a plaster fragment that had fallen from the western slope, and sodium chloride crystals have formed on the paintings. In ESEM-EDX analysis of a plaster cross section (fig. 6), sodium chloride is shown to have accumulated at cracks and fissures in the plaster, whereas sulfur (from sulfate) is notably

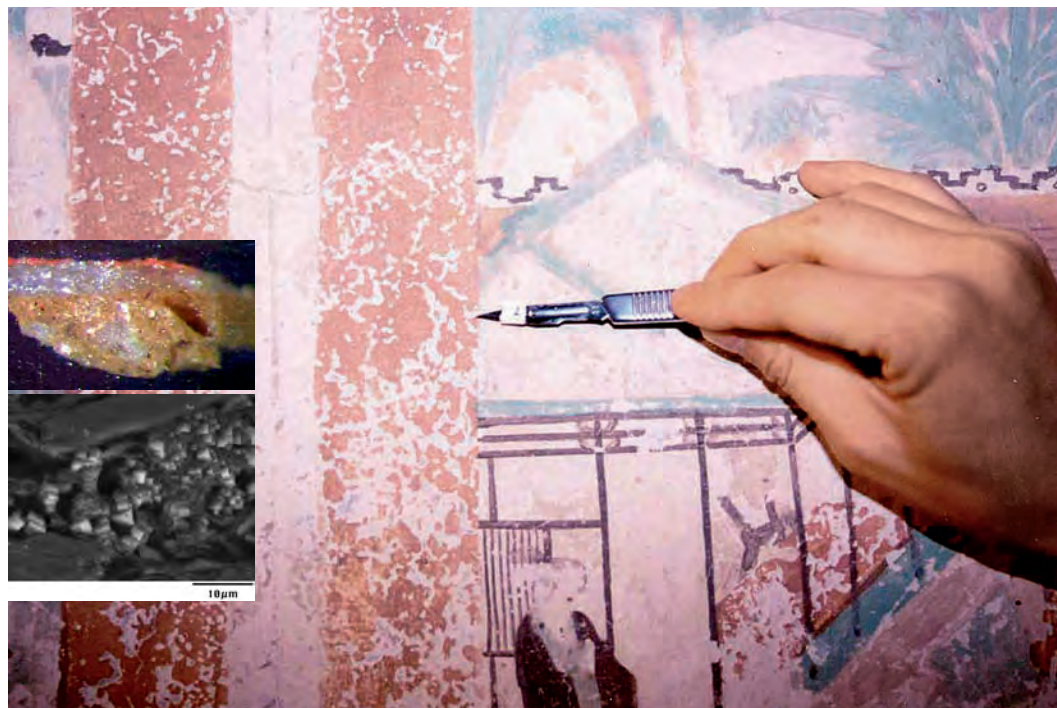


FIGURE 7 Punctate eruption of sodium chloride crystals between the red paint and ground layers in sample 85NQ98PE2. (a) Darkfield photomicrograph of paint cross section; (b) ESEM enlargement showing cubic crystals of sodium chloride.

absent. Moreover, bands of sodium chloride are visible in the elemental maps just slightly beneath the painted surface, showing that the salt is more concentrated in that region. This is consistent with the plaster microcore data.

The appearance of small, rounded holes in the paint layer is a common phenomenon in cave 85. Defined in this project as “punctate eruption,” it is most obvious on dark red stripes and bands (fig. 7), although to a lesser extent it affects other colors, including the ground. In order to understand more fully the cause of this phenomenon, ESEM was used to examine a cross-section sample taken from a dark red stripe on the south wall. In this sample, crystals of sodium chloride were observed between the red paint layer and the ground. As sodium chloride crystals form between the paint and ground layers, eventually they break through the paint and leave small losses.

Gypsum deposits have also been reported on the wall paintings and plaster layers in certain caves at Mogao (Kuchitsu and Duan Xiuye 1997). These deposits were attributed to the reaction between the soluble sulfate from the hygroscopic salts and calcium-rich minerals present in the paint and ground layers. Gypsum was detected in cave 85, primarily in association with the red organic colorants, although it is not clear if gypsum was intention-

ally used in the process of precipitating the dyestuffs into the form of pigments.

Conclusion

Several valuable lessons can be learned from the experiences of the analytical research team working on the cave 85 project. One of the most important aspects of the process was the careful examination of the wall paintings for the purpose of selecting representative samples; sturdy scaffolding and adequate task lighting were essential for eventual success due to the nonuniform condition of the paintings throughout the cave. The examination, carried out by experienced wall painting conservators, often involved discussions with conservation scientists. Without truly representative samples accompanied by thorough documentation of the sample location, it would have been impossible to obtain accurate results, even with the finest laboratory equipment.

The dictum “Do as much as necessary but as little as possible” certainly pertains to analytical investigations of wall paintings. It is hard to imagine exhausting the research possibilities that are presented by the masterpieces of Tang dynasty wall painting in cave 85, let alone those afforded by every painted cave temple in the Mogao Grottoes.

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Notes

- 1 The laboratory facilities at the Dunhuang Academy house X-ray diffraction (XRD) for identification of mineral pigments, and Fourier transform infrared spectrometry (FTIR) for analysis of minerals, natural organic materials, and synthetic polymers. Over the course of the project, a program of staff exchanges gave several Dunhuang Academy scientists opportunities to conduct research on specialized equipment at the GCI. Their studies featured environmental scanning electron microscopy with energy-dispersive X-ray spectrometry (ESEM-EDX) for mapping elemental distributions within paint cross sections, identification of animal glue and plant gum binding media using GC-MS, analysis of organic colorants using high-performance liquid chromatography/photodiode array-mass spectrometry (LC-PDA-MS), and soluble salt analysis using ion chromatography (IC). In addition, GCI scientists conducted advanced workshops at the Dunhuang Academy on the use of polarized light microscopy (PLM) for identifying mineral pigments in dispersions of paint particles, preparation and examination of paint cross sections for revealing painting technique, and use of ion-selective electrodes and test strips for salt analysis.

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Asian Organic Colorants: A Collaborative Research Project

Cecily M. Grzywacz, Jan Wouters, Su Bomin, and Fan Yuquan

Abstract: *The presence of organic colorants has been reported on the wall paintings at Mogao Grottoes by the cave 85 project team. To address the challenges of identifying these organic colorants, a collaborative multiyear project was begun in 2006 between the Getty Conservation Institute, Jan Wouters, Belgium, and the Dunhuang Academy. Determining specific organic colorants that could have been used in China is a challenge because the biological sources used to produce the dyes and pigments frequently are unique to the geographic region. This paper describes the Asian organic colorants project and the experimental design used to develop a systematic strategy for the analysis of Asian organic colorants. The Mogao Grottoes wall painting colorants will ultimately be determined using this strategy.*

The analytical research conducted by the Getty Conservation Institute (GCI) at the Mogao Grottoes generated a wealth of information on the mineral pigments and binding media used in these caves, especially cave 85 (see Schilling et al., this volume). Shekede and other conservators working at the site have also reported the use of organic colorants and washes as a final layer in the caves (see Shekede et al., this volume). As the use of organic colorants is recognized by conservators throughout Asian wall paintings, there is an increasing need to determine which biological sources were used to prepare them. This will provide crucial information for the preservation of the wall paintings and lead to a better understanding of painting techniques and the ability to decipher the original painted image (Yamauchi, Taniguchi, and Uno 2007: 120). Determining specific organic colorants that could have been used in China requires identification of the biological sources used to produce the dyes

and pigments, which most likely were unique to the geographic region.

To address these questions a collaborative research project was initiated between the GCI, consultant Jan Wouters, and the Dunhuang Academy. The Asian organic colorants (AOC) project is a systematic, multiyear scientific research effort to develop a strategy for the analysis of traditional Chinese organic colorants used as textile dyes and organic pigments in wall paintings, in China and beyond. Detection and identification of these colorants present a challenge not only because many of the biological sources used to create them have not been well studied but also because, in the case of paints prepared with organic pigments, the concentrations of the colorants are relatively low compared to those of inorganic pigments and binding media. The AOC project is expected to generate knowledge that will resolve some remaining problems with identification of natural organic colorants in Asia, reported in former studies (Wouters 1994, 1997, 1998).

The project has five components:

1. Thorough literature search on Chinese biological sources, painting techniques, and analysis methods.
2. Acquisition of selected plant and insect materials to prepare reference samples.
3. Making paints of the organic pigments and applying them on painted plaster coupons that replicate the stratigraphy of the wall paintings at the Mogao Grottoes.
4. Analysis of reference samples and the coupons to determine their diagnostic value and development

of an analytical strategy to identify Asian organic colorants.

5. Application of this analytical strategy to historical samples from the Mogao Grottoes.

Literature Search

A literature search was mandatory to determine which biological sources may have been used on the Mogao Grottoes wall paintings and polychrome sculpture (Grzywacz et al. 2008). Searches of Art & Archaeology Technical Abstracts (AATA), Bibliographic Conservation Information Network, Scopus, SciFinder, and World of Science resulted in nearly 900 abstracts. These were screened, and more than 500 relevant papers and books were read. One hundred fifty different biological sources were found, often as botanically identified genus or species or sometimes using common nomenclature. Citations from independent references for biological sources were counted to identify the most frequently cited ones. Thirty source groups were selected. Some groups refer to a species, even when relevant citations in the literature did not; for example, citations of safflower undoubtedly refer to *Carthamus tinctorius* L. and were classified and counted as such. However, confusion arose with the species identifications of madder (*Rubiaceae* family) and plants producing indigoid dyes (*Indigofera*, *Isatis*, *Strobilanthes*, *Polygonum* genuses). For those groups, species were selected that were most suggestive for the region, based on botanical encyclopedic references (Bensky et al. 2004; Cardon 2007; Fèvre and Métaillé 2005; Huxley, Griffiths, and Levy 1999; Jiaju Zhou et al. 2003; Mabberley 1993; Wu Zhengyi, Raven, and Hong Deyuan 2008) and on a 2006 interview with Jingwu Wang, botanist, Beijing University.

Currently, the AOC bibliography contains more than 250 articles, books, and online resources. In addition to biological sources, data on recipes, painting techniques, and historical context were collected. A list of key literature on analysis and identification of Asian organic colorants has also been compiled. It will be published as an AATA bibliography, available on the GCI Web site.

Biological Sources and Acquisitions

An initial thorough literature search conducted on biological sources used to produce organic colorants revealed the most likely ones for the production of organic colorants used in Asia, specifically China and hence at the Mogao Grottoes.



FIGURE 1 Shopping for biological sources at a pharmacy in Dunhuang, Gansu province, China.

A total of 108 different biological sources were identified, but based on the frequency of independent citations, 36 biological sources, belonging to 30 groups, were selected for study. Table 1 is a complete list of the selected groups of AOC biological sources.

Plants and resins identified for paint production and analysis were purchased at pharmacies in Dunhuang and Beijing and at Chinese pharmacies in the Los Angeles area (fig. 1). Items not available at pharmacies were acquired from botanical gardens in the United States and China. Some sources were purchased at the chemical market in Old Delhi, India.

Preparations

Bulk reference samples were prepared from each biological source, using historical recipes when available (fig. 2). When



FIGURE 2 Series of AOC reference samples prepared from *Gardenia augusta* L. From left to right: dyed wool, dyed silk, cake and pigment.

Table 1 Biological Sources Used to Produce Asian Organic Colorants in Order of Number of Citations

Dye Group; Prominent Color	Citations	Common Name of Species	Chinese Name	Pinyin	Genus	Species and Author [synonym(s)]
Indigoid; blue	55	conehead	板蓝	ban lan	<i>Baphicacanthus</i>	<i>cusia</i> (Nees) Bremekamp [<i>Strobilanthes cusia</i> (Nees) O. Kuntze, Ma Lan Gen 马蓝 = <i>Strobilanthes flaccidifolius</i> Nees]
		wild indigo, West Indian indigo	野青树	ye qing shu	<i>Indigofera</i>	<i>suffruticosa</i> Mill
		dyer's indigo	木蓝	mu lan		<i>tinctoria</i> L.
		indigo woad, Chinese indigo	大青叶	da qing	<i>Isatis</i>	<i>indigotica</i> Fort.
		dyer's woad	菘蓝	song lan		<i>tinctoria</i> L.
Chinese indigo	蓼蓝	liao lan	<i>Polygonum</i>	<i>tinctorium</i> Ait. [<i>P. tinctorium</i> Lour.; <i>Persicaria tinctoria</i> (Ait.) Spach]		
Madder; red	27	Japanese madder	日本茜草	ri ben qian cao	<i>Rubia</i>	<i>akane</i> Nakai
		Indian madder, Chinese madder, munjeet	茜草炭 or 茜草	qian cao gen or qian cao		<i>cordifolia</i> L. [<i>R. munjista</i> Roxb.]
		European madder; munjeet	杨茜草	yang qian cao		<i>tinctorum</i> L.
Safflower; salmon red	23	safflower	红花	hong hua	<i>Carthamus</i>	<i>tinctorius</i> L.
Redwood; red	18	redwood; brazilwood	苏木	su mu	<i>Caesalpinia</i>	<i>sappan</i> L.
Shikon; purple	17	red root Gromwell	紫草	zi cao	<i>Lithospermum</i>	<i>erythrorhizon</i> Sieb. & Zucc.
		pearl Gromwell	小花紫草	xiao hua zi cao		<i>officinale</i> L.
Japanese pa- goda tree; yellow	17	Chinese yellow berries	槐花	huai shu	<i>Sophora</i>	<i>japonica</i> L. [<i>Styphnolobium</i> <i>japonicum</i> (L.) Schott]
Gardenia; yellow	14	Cape jasmine	梔子	zhi zi	<i>Gardenia</i>	<i>jasminoides</i> Ellis [<i>G. augusta</i> (L.) Merrill; <i>G. florida</i> L.]
Amur cork tree; yellow	13	amur cork tree	黄柏	huang bai	<i>Phellodendron</i>	<i>amurense</i> Ruprecht
Buckthorn; yellow	13	common buckthorn	药鼠李	yao shu li	<i>Rhamnus</i>	<i>catharticus</i> L.
			鼠李	shu li		<i>chlorophorus</i> Decne. ex Hemsl.
		Davurian buckthorn	鼠李	shu li		<i>davurica</i> Pallas
		Chinese buckthorn	冻绿	dong lu		<i>utilis</i> J. Descaisne
Gamboge; yellow	12	rattan yellow	藤黄树	teng huang shu	<i>Garcinia</i>	<i>hanburyi</i> Hook. f.
			藤黄	teng huang ke		<i>morella</i> Gaertn.
Turmeric; yellow	9	common turmeric	姜黄	jiang huang	<i>Curcuma</i>	<i>longa</i> L. [<i>C. domestica</i> Valetton]
			郁金	yu jin		<i>aromatica</i> Salisbury
			温郁金	wen yu jin		<i>wenyulin</i> YH Chen & C Ling

Table 1 (cont.)

Dye Group; Prominent Color	Citations	Common Name of Species	Chinese Name	Pinyin	Genus	Species and Author [synonym(s)]
Lac; red	9	Indian lac	紫胶虫	zi jiao chong	<i>Kerria</i>	<i>lacca</i> Kerr [<i>Laccifer lacca</i> Cockerell]
Young fustic; yellow	7	young fustic	黄栌	huang lu	<i>Cotinus</i>	<i>coggygia</i> Scopoli [<i>Rhus cotinus</i> L.]
			灰毛黄栌	hui mao huang		<i>coggygia</i> var. <i>cinerea</i> Engler [<i>C. cinerea</i> (Engler) FA Barkley]
Silver grass; yellow	7	Chinese silver grass	芒萁	mang jing	<i>Miscanthus</i>	<i>sinensis</i> Andersson
		Dyeing silver grass	青茅	qing mao		<i>tinctorius</i> (Sieb. ex Steud.) Hack.
Barberry; yellow	5	Japanese barberry	日本小檗	ri ben xiao bo	<i>Berberis</i>	<i>thunbergii</i> DC
		S. China Mahonia; Japanese Mahonia	台湾十大功劳	tai wan shi da gong lao	<i>Mahonia</i>	<i>japonica</i> (Thunb.) DC [<i>Berberis japonica</i> (Thunb.) R. Br.]
				hua nan gong lao mu		
Joint grass; yellow	4	hairy jointgrass; small carpgrass; kobuna-gusa (Jap.)	菴草	jin cao	<i>Arthraxon</i>	<i>hispidus</i> (Thunb.) Makino
Walnut; brown	4	walnut	胡桃	hu tao	<i>Juglans</i>	<i>regia</i> L.
Sandalwood; red	4	red sandalwood	紫檀		<i>Pterocarpus</i>	<i>santalinus</i> L. f.
Oak; beige	4	sawtooth oak	麻栎	ma li	<i>Quercus</i>	<i>acutissima</i> Carruthers
Rhubarb; red	4	rhubarb	药用大黄 or 大黄	yao yong da huang or da huang	<i>Rheum</i>	<i>officinale</i> Baillon
			掌叶大黄	zhang ye da huang		<i>palmatum</i> L.
			鸡爪大黄	ji zhua da huang		<i>tanguticum</i> (Max. ex Regel) Max. ex Balfour
Tannin; gray to black	4	Chinese sumac	盐麸木	yan fu mu	<i>Rhus</i>	<i>semialata</i> Murray = <i>Rhus chinensis</i> Miller
Coptis; yellow	3	Chinese goldthread	黄连	huang lian	<i>Coptis</i>	<i>teeta</i> var. <i>chinensis</i> (Franch.) Finet & Gagnep. [<i>C. chinensis</i> var. <i>chinensis</i> ; <i>C. chinensis</i> Franch.]
			云南黄连	yun nan huang lian		<i>teeta</i> Wallich [<i>C. teetoides</i> CY Cheng]
		Japanese goldthread	胡黄连 日本 黄连	hu huang lian ri ben huang lian	<i>Neopicrorhiza</i>	<i>scrophulariiflora</i> (Pennell) DY Hong [<i>Picrorhiza scrophulariiflora</i> Pennell; <i>Coptis japonica</i> Makino]
Saffron; yellow	3	saffron	番红花	fan hong hua	<i>Crocus</i>	<i>sativus</i> L.
Larkspur; yellow	3	yellow larkspur			<i>Delphinium</i>	<i>semibarbatum</i> Bien. ex Boiss.
Bayberry; yellow	3	red bayberry, Chinese bayberry	杨梅	yang mei	<i>Myrica</i>	<i>rubra</i> Sieb. & Zucc.

Table 1 (cont.)

Dye Group; Prominent Color	Citations	Common Name of Species	Chinese Name	Pinyin	Genus	Species and Author [synonym(s)]
Dragon's blood; red	3	Dragon's blood	血竭	xue jie	<i>Daemonorops</i>	<i>draco</i> Blume
		Socotra dragon tree	血竭 of 珠红龙血树 (剑叶龙血树)	zhu hong long xue shu (jian ye long xue shu)	<i>Dracaena</i>	<i>cinnabari</i> Balf. f.
		Cambodia dragon tree	血竭 of 海南龙 血树	hai nan long xue shu		<i>cambodiana</i> Pierra ex Gagnepain
		sword-leaved dragontree	血竭 of 剑叶龙血树	jian ye long xue shu		<i>cochinchinensis</i> (Lour.) SC Chen
Bedstraw; red	3	Our Lady's bedstraw	篷子菜		<i>Galium</i>	<i>verum</i> L.
Four o'clocks; red	3	marvel of Peru; shower flower	紫茉莉	zi mo li	<i>Mirabilis</i>	<i>jalapa</i> L.
Wash; no color	1	pearlwort	根叶漆姑草	gen ye qi gu cao	<i>Sagina</i>	<i>maxima</i> A. Gray
Carbon black; black	ink	princess tree, tong tree	毛泡桐	mao pao tong	<i>Paulownia</i>	<i>tomentosa</i> (Thunb.) Steud.
		ink	膜	mo	Various sources of poorly specified origin	

these were unavailable, modern laboratory practice, based on aqueous extractions and fermentations only, were used to prepare the samples. Dyeing of wool and silk was performed with or without preliminary mordanting with alum, depending on the chemical nature of the dyes. Occasionally, dyed cotton or paper was prepared. Pigments were prepared on a hydrated aluminum oxide base. Paints were prepared by suspending pigments in a diluted animal glue or fruit tree gum medium or by concentrating the dye extract and adding glue. Cakes were prepared by drying and hence concentrating

the dye extract. All preparations are documented and reference samples cataloged in a database.

One hundred forty painted plaster coupons, 15 centimeters in diameter, replicating the stratigraphy of the Mogao wall paintings were prepared by the Dunhuang Academy using clay and other materials available at Mogao. Each coupon has a traditional ground layer applied to half of its surface, overlaid with seven stripes of common inorganic paints used in the grottoes (fig. 3a). Organic paints prepared with the reference pigments were applied on the painted plaster cou-

FIGURE 3 (a) Blank painted plaster coupon as received from the Dunhuang Academy. (b) Coupon with *Gardenia augusta* pigment paints in gum and animal glue applied.



(a)



(b)

pons (fig. 3b). The plaster, ground, inorganic paints, and lake pigments provide crucial combinations for evaluating an analytical scheme. From each biological source, four mock-ups are produced: two for investigating the best possible analytical procedure(s), one for accelerated aging at the GCI, and one that will be kept in the GCI reference collection for future research.

Analytical Strategy

The development of a strategy for the analysis of organic dyes on yarns and organic pigments in paint requires consideration of the following parameters: level of destructiveness to both the object and the sample, diagnostic value, sensitivity, and reproducibility. High-performance liquid chromatography/photodiode array-mass spectrometry (HPLC-PDA-MS) is routinely used for analysis of organic dyes and pigments present in artifacts produced in Europe and the Americas. Its use in an Asian, or, more specifically, Chinese, context cannot necessarily be extrapolated because the majority of biological sources identified in Chinese artifacts were different from those found in the European and American artifacts. HPLC-PDA-MS will probably remain the core analytical technique because of its high diagnostic value, sensitivity, and reproducibility. The method used by the GCI will be optimized for the analysis of Asian organic dyestuffs and pigments. It will result in a library of ultraviolet-visible (UV-Vis) spectra for color-contributing components and an ion trap electrospray ionization negative ion mode (ESI-NIM) and positive ion mode (ESI-PIM) mass spectral database of the same diagnostic components of organic colorants that includes both MS and MS-MS spectra.

Additional techniques will be investigated for their ability to identify important information not adequately detected through HPLC-PDA-MS and for their ability to be less destructive on the object and sample. The project will consider the following additional analytical techniques: in-situ UV-induced fluorescence imaging (Verri 2007), microspectrofluorimetry (Claro et al. 2008), Raman spectroscopy and surface enhanced Raman spectroscopy (SERS) (Leona, Stenger, and Ferloni 2006), direct temperature-resolved mass spectrometry, and 3D-UV-Vis fluorescence spectroscopy.

Historical Samples

Once the analytical strategy is verified, historical samples from wall paintings at the Mogao Grottoes will be analyzed

and studied. The strategy will also be applicable to Asian dyestuffs used in textiles and Asian organic pigments used in paintings. The results of this research project should have far-reaching ramifications for the study of the cultural heritage in China and throughout the region. (For more information, see www.getty.edu/conservation/science/asian/index.html.)

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Evaluating the Light Sensitivity of Paints in Selected Wall Paintings at the Mogao Grottoes: Caves 217, 98, and 85

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Abstract: *Damage to the Mogao Grottoes from increased tourist visitation is a major concern to those responsible for protecting and interpreting the site. Threats include light damage to wall paintings caused by new artificial illumination, intended to improve the visitor experience. We evaluated this threat using a xenon arc lamp exposure apparatus on small samples provided from three representative caves (217, 98, 85) with painted walls. Samples had been characterized previously by Fourier transform infrared spectroscopy, Raman spectroscopy, scanning electron microscopy, and polarized light microscopy. The paintings were known to contain both inorganic mineral-based pigments and organic pigments, thought to be of the “lake” variety. Some paint samples were mixtures of both pigment types. Color-fading analysis showed a reasonable expectation that, except in one case, the organic pigments were no longer at high risk for continued rapid fading but that certain inorganic pigments already darkened from light exposure could be expected to continue this darkening trend. A long-term monitoring program, responding to future use of the Mogao Grottoes, is recommended.*

Color science has many tools for understanding the composition, structure, and stability of cultural artifacts. Their versatility, nondestructive nature, and sensitivity have been and will continue to be useful in informing preventive conservation decision making. One important aspect that bears on our immediate interest in the Mogao Grottoes is how color science informs risk assessment decision making in anticipating future risks and damages. In the Mogao Grottoes, Schilling (pers. com. 2005) observed that the color integrity and aesthetic harmony of the paintings diminish gradually as one advances toward cave openings from the darker inte-

rior spaces. Inversely, the paintings become brighter, contain richer hues, and are generally far better preserved in areas where less natural daylight has intruded. Often these effects can be dramatic. When these observations are untangled from other forms of deterioration, the hypothesis emerges that light has been partially responsible for the observed changes. Analysis of paint samples supports light’s historic involvement, and the question arises, Are the cave paintings still sensitive to light?

The sensible approach to assessing light sensitivity often employed in museums is to identify the components of an object and then carry out accelerated aging on modern analogs of those identified components. It would be far better in the Mogao Grottoes to assess light sensitivity directly on the actual wall paintings or on samples taken from the walls. In the 1990s a new instrument, the microfader, was designed and produced to address this need (Whitmore, Xun Pan, and Bailie 1999). Whitmore gives a detailed description of how the instrument functions and includes a list of parts, enabling the construction of the instrument. Several versions of the microfader have been assembled from standard optical components, including two built at the Getty Conservation Institute. Briefly, the source of illumination, a 75-watt xenon arc lamp, is filtered to remove the ultraviolet and infrared regions of the spectrum to reasonably match a filtered light source that could be used to display the artifact. The microfader focuses approximately 1 lumen on a spot 0.4 millimeter across. Since highly sensitive colorants fade predominantly from visible wavelengths (McLaren 1956), the instrument works very quickly—often a period of only 10 to 15 minutes is required per test exposure. For moderately sensitive materials, it is easy to extend the duration of

Table 1 Summary of Experimental Data and Blanks from Cave 85

Sample ID	Description	ΔE^*_{94} (30 min)	ΔE^*_{94} (60 min)	Results
Cave 85 S01	East wall, southeast corner. Plum-colored layer over white ground, probably an organic lake.	0.4	–	Possible change \geq BW3
Cave 85 S027	Green layer. Azurite transformation to atacamite suspected.	0.1	0.2	No detectable change
Cave 85 S019	Pinkish organic colorant. No Fe, Hg, or Pb.	0.2	0.2	No detectable change
Cave 85 S021	South wall, east side. Brown translucent color. Possible mix or organic lake (FTIR) with cinnabar (SEM-EDX).	0.6	0.7	Possible change \geq BW3
Cave 85 S02	Similar location to S01. Dark plum-colored organic lake (TLC) pigment over black.	0.5	0.45	Possible change \geq BW3
Cave 85 S028	Ceiling panel, east side. Definite red lead and cinnabar (SEM-EDX).	1.7	2.6	Definite change = BW2–3
ISO BW1	ISO Blue Wool #1 Standard	5.5	8.1	
ISO BW2	ISO Blue Wool #2 Standard	2.9	4.0	
Blank 1	Chrome oxide pigment in acrylic paint binder	≈ 0.1	≈ 0.30	
Blank 2	Raw umber in acrylic paint binder	≈ 0.1	≈ 0.02	
Blank 3	Deep Pink (British Ceramic Research Association) Standard	≈ 0.2	≈ 0.2	
Blank 4	Deep Pink (British Ceramic Research Association) Standard	≈ 0.1	≈ 0.1	
Detection Limit		0.4	0.6	

testing into the range of 5 million to 10 million lux-hours, or 30 to 60 minutes of device operation and even longer. Normally, estimates of lightfastness would then be adjusted to the behavior of well-characterized standards such as the ISO Blue Wool Standards (ISO 105-A01, 1994) run at the same time as the unknown colorants.

Light through the microfader is reflected, collimated, filtered, and focused onto a quartz fiber optic cable and routed normally to the area being tested. Reflected light is intercepted at a 45-degree angle ($0/45^\circ$ geometry) and via a second quartz fiber optic cable directed to a spectrophotometer. From there it is relayed to a computer for further processing and storage. Thus the instrument fades and measures color simultaneously.

Since future plans for the Mogao Grottoes include enhancing internal artificial lighting for visitor satisfaction, an assessment of illumination risks is important. Below we

describe our use of the microfader apparatus to determine the light sensitivity of samples from wall paintings in three representative locations: caves 217, 98, and 85.

Methods

Samples

We examined a total of 14 small (<2 mm diameter) samples of paint from wall paintings: 6 samples from cave 85, 4 samples from cave 217, and 4 samples from cave 98. The location and approximate composition of these paint samples are summarized in table 1 for cave 85 and in table 2 for caves 217 and 98. For the analyses, we also used three fading standards and eight controls. Samples had been characterized previously by Fourier transform infrared (FTIR) spectroscopy, Raman spectroscopy, scanning electron microscopy (SEM-EDX), and polarized light microscopy.

Table 2 Summary of Experimental Data and Blanks from Caves 217 and 98

Sample ID	Description	ΔE^*_{94} (30 min)	ΔE^*_{94} (60 min)	Results
Cave 217 E01	Red. North of east wall; 94 cm from north wall, 73 cm from ground. Vermilion detected by Raman spectroscopy.	0.5	0.8	Definite change = BW2-3
Cave 217 E02	Yellow. South of east wall; 23 cm from south wall, 43 cm from ground. Geothite detected by Raman spectroscopy.	0.3	0.2	No detectable change
Cave 217 E03a	Brown. South of east wall; 27 cm from south wall, 36 cm from ground. Unidentified fluorescence from Raman spectroscopy.	1.6	2.3	Definite change = BW2-3
Cave 217 E03b	Same as above.	1.4	1.7	Definite change = BW2-3
Cave 217 E03c	Same as above.	1.6	2.3	Definite change = BW2-3
Cave 217 E03 Average	Same as above.	1.8 ± 0.47	2.1 ± 0.35	Definite change = BW2-3
Cave 217 E04	Light red. North of east wall; 12 cm from north wall, 119 cm from ground. Hematite detected by Raman spectroscopy.	0.05	0.2	No detectable change
Cave 98 E01	Brown. South of east wall; 178 cm from south wall, 60 cm from ground. Oxylates, sulfates, quartz, mica, calcite detected by FTIR.	0.5	0.8	No detectable change
Cave 98 E02	Red. South of east wall; 121 cm from south wall, 101 cm from ground. Same FTIR results as for 98-E01.	0.2	0.3	No detectable change
Cave 98 E03	Orange. East of south wall; 127 cm from east wall, 126 cm from ground. Same FTIR results as for 98-E01.	0.2	0.3	No detectable change
Cave 98 E04a	Red. South of east wall; 88 cm from south wall, 376 cm from ground. Same FTIR results as for 98-E01.	0.3	0.3	No detectable change
Cave 98 E04a	Red. South of east wall; 88 cm from south wall, 376 cm from ground. Same FTIR results as for E01.	0.4	0.4	Possible change \geq BW3
ISO BW1	ISO Blue Wool #1 Standard	5.5	8.0	
ISO BW2	ISO Blue Wool #2 Standard	2.8	4.0	
ISO BW3	ISO Blue Wool #3 Standard	0.4	0.6	
Blank 1	Raw umber in acrylic paint binder.	≈ 0.1	≈ 0.2	
Blank 2	Raw umber in acrylic paint binder.	≈ 0.1	≈ 0.1	
Blank 3	Raw umber in acrylic paint binder.	≈ 0.2	≈ 0.1	
Blank 4	Raw umber in acrylic paint binder.	≈ 0.1	≈ 0.1	
Detection limit	From raw umber blanks (average + 3* S.D.)	0.4	0.6	

Experimental Setup and Approach

For our microfader testing on paint microsamples from caves 217, 98, and 85, the spectrometer was calibrated with a Spectralon (PTFE) white reference standard and dark current immediately prior to each sample. On the few occasions that it was possible, up to three one-hour-long replicate runs were averaged. Usually samples were provided with only enough surface area for a single measurement. A spectrum was acquired every 10 milliseconds, and 10 spectra were averaged at a time. Every 60 seconds the most current averaged spectrum was saved to disc. The 2° observer and D65 Illuminant were used.

Typically color change is evaluated by converting the full spectral curve from 380 to 780 nanometers to a three-dimensional color space that matches the manner in which the human eye responds to visible light. This color space was defined by the Commission Internationale de l'Éclairage (Berger-Schunn 1994)¹ and is used to calculate a value of color difference termed “ ΔE .” After having calculated a curve of color change (ΔE^*_{94}) versus time of exposure, it is necessary to interpret the results compared to known fading standards. As indicated earlier, we used the ISO Tests for Color Fastness (ISO 105-A01, 1994) as the basis for comparison.

Cave 85

Analysis

We had five pigment assignments for cave 85. Based on SEM-EDX, FTIR spectroscopy, Raman spectroscopy, and thin layer chromatography (TLC), identifiable pigment compositions were classified as (1) an organic lake, (2) a green copper-based mineral, (3) cinnabar (vermilion, mercury sulfide, α -HgS), (4) red lead (Pb_3O_4), and (5) carbon black. Samples So1, So2, So19, and So21 contained some portion of organic colorant. Cinnabar was also found in So21, and cinnabar and red lead were attributed to the pigment in So28. Sample So27 had a green layer assumed to be the transformation from azurite to atacamite ($Cu_2(OH)_3Cl$). The lone black attribution for carbon black was seen in sample So2.

The responses of the samples to microfading were expected to be small, owing to the great age of the wall paintings, so the duration of exposure was lengthened from ten minutes to an hour. The instrumental design has a noted drift, so we measured the color stability of three types of blanks: chrome oxide in an acrylic emulsion paint and raw umber in an acrylic emulsion paint (both Golden Paints) and

Deep Pink ceramic color tile (Ceramic Color Standards—Series II, British Ceramic Research Association/National Physical Laboratory). The detection limit was determined as the average ΔE^*_{94} for all blanks and their replicate measurements after 30 and 60 minutes, plus three times the standard deviation (Taylor 1997).

Results

Figure 1 summarizes the results of the cave 85 samples (So1, So2, So19, So21, So27, So28) and the fading standards (BW1–3). The detection limit is indicated as a solid red line (30 min.). Samples So19 and So27 are below the detection limit. Data are not shown for 60 minutes, since they were still below the 60-minute limit at twice the light exposure. The lack of response for So27 is not surprising as it is a green copper-based mineral and should no longer be expected to be sensitive to light, if indeed it ever was. Samples So1 and So2 are plum colored and were assigned as organic (probably a lake pigment) on the basis of their infrared spectrum, yet the change is detectably borderline. One would conclude that assigning this pigment as an organic lake is probably correct for So1 and So2 but that the present and future lightfastness is no longer limited to the higher sensitivity of Blue Wool 1–2 range but rather lowered to as much as Blue Wool 3 or 4, as is often the case with aged colorants. The same sensitivity can be ascribed to So21.

Sample So28, analyzed by SEM-EDX, contained mercury and lead, which presumably represents the pigments vermilion (from ground cinnabar) and red lead used by the

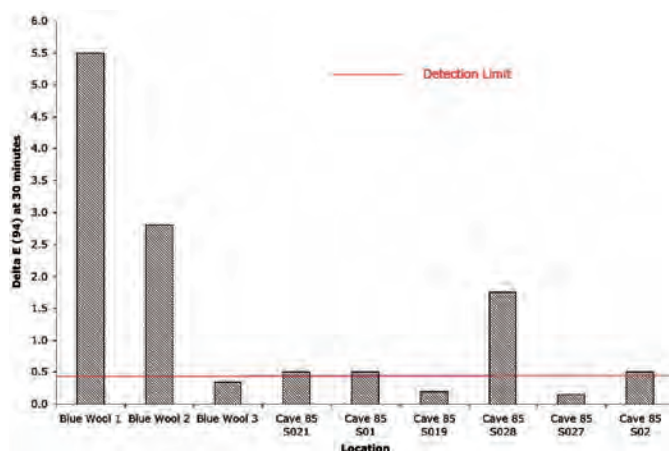


FIGURE 1 All data for cave 85 at 30 minutes.

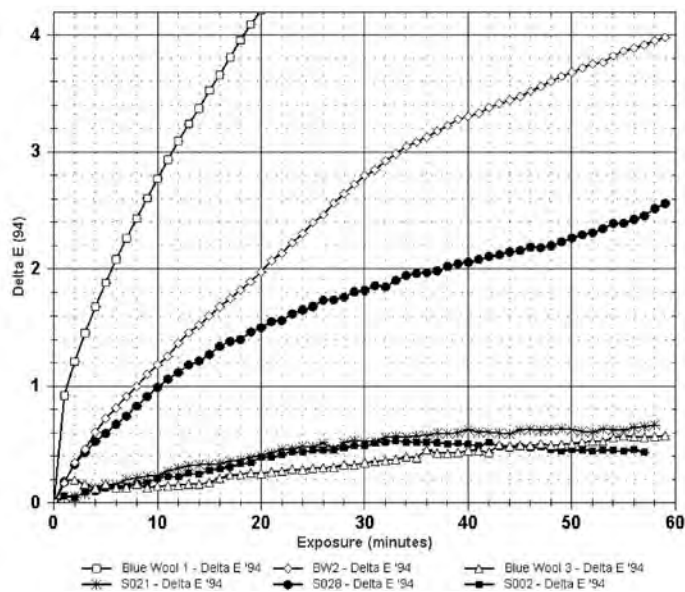


FIGURE 2 Cave 85, 60-minute comparison of ISO Blue Wools 1–3 and So02 (possible change \geq BW3), So21 (possible change \geq BW3), So28 (definite change = BW2–3).

original artists. It is not uncommon to find both cations present in a paint sample. So28 demonstrated the largest color change, $2.6 \Delta E_{94}^*$. Figure 2 graphically compares So28 to the fading standards and to two marginally reactive samples. Cinnabar (mercuric sulfide, vermilion, α -H₂S) has been known to darken from photo-induced effects since Roman times (Feller 2002).² The literature has many contradictory references to the lightfastness of vermilion, ranging from moderately permanent to unstable. During the National Gallery of Art Project carried out in the 1950s, many of the test panels of vermilion oil paints darkened within five years after approximately 650,000 lux-hours of diffuse daylight gallery exposure (Feller 2002).³

That red lead darkens from light exposure may be more complex. In fact, red lead exhibits a strong relative humidity dependency on the type of color change it undergoes. Saunders and Kirby (2004) subjected lac lake, red lead, azurite, and verdigris to 22,000 lux of illumination at 11, 32, 51, 75, and 90 percent relative humidity (RH). Darkening was most distinct for red lead at 11 percent RH and 32 percent RH, and the overall color change was toward lightening above 50 percent RH. Below 50 percent RH, the mechanism is thought to be a persistent increase of lead (IV) oxide from lead (II, IV) oxide. Above 50 percent RH, the reaction is driven to basic

lead (II) carbonate (lead white). Since the microfader presumably dries the faded spot (at about 40–48°C), the reaction logically follows the darkening pathway and is likely the same thing happening in cave 85 and elsewhere in Mogao. This underlines the complexity of Mogao cave painting deteriorations.⁴

Caves 217 and 98 Analysis and Results

Table 2 summarizes the samples and results for caves 217 and 98. Figure 3 shows the reactivity of sample E03, which had been supplied in a large enough quantity to conduct three measurements. No definitive chemical identification could be made on this sample, but an unidentified fluorescence was detected with Raman spectroscopy. E03 data represented ΔE_{94} as averaging 2.1. This is on a par with the most reactive sample examined in cave 85, but this “brown” sample shows all the colorimetric indications of undergoing a typical organic pigment fading-type reaction.⁵ However, sample E01, which did have mercury, continues the darkening noted for the other mercury-containing pigment sample (So28), even though the magnitude of the changes is smaller. For cave 98, none of the wall painting samples showed a detectable color response. Figure 4 plots all the data after 30 minutes for caves 217 and 98.

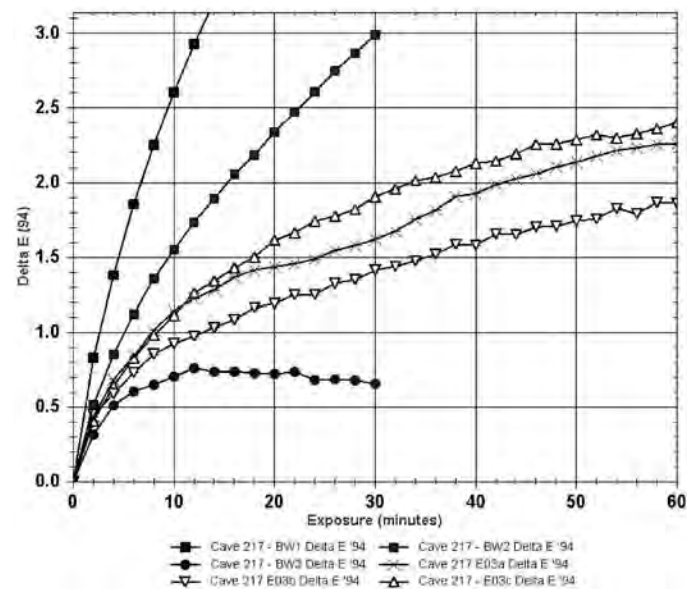


FIGURE 3 Data from cave 217 for three replicate measurements of sample E03.

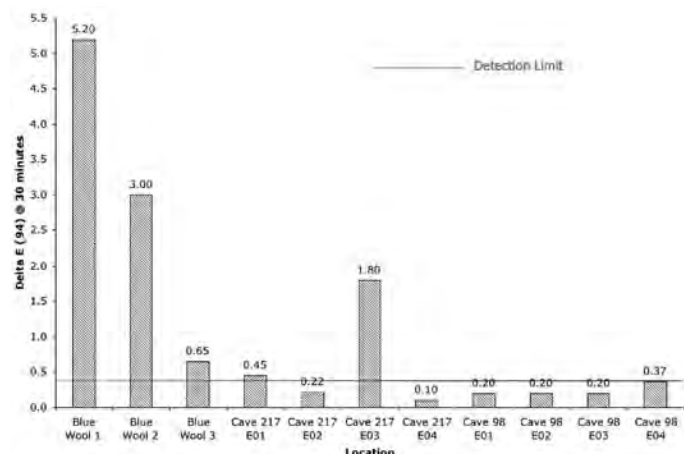


FIGURE 4 All data from caves 217 and 98.

Discussion

Taken together, the results from the three Mogao caves form a cohesive grouping, but they are still rather incomplete given the total extent of the wall paintings. Sample E03 from cave 98 was large enough to permit three replicate measurements. Since this sample represents one of the largest color changes, three replicates leave no doubt about the interpretation.

Half of the fourteen samples showed no change when exposed to nearly 6.8 million lux-hours of light. The remaining half of the samples suggested a possible or definite change; of those seven samples, three (21.4% of total) showed definitive changes ranging from 4.5 to 7.5 times the detection limit. As indicated in the experimental section, detection limits are determined by adding three times the standard deviation to the sample mean. Even then, terms such as *possible* and *probable* were used in reference to light sensitivity until the change was so large that it exceeded detection limits arbitrarily chosen to include five times the standard deviation added to the blank mean. Thus half the sample locations examined contained pigment components that were demonstrably light-sensitive—three for which a known sensitive inorganic pigment was detected, two with an organic pigment determined by TLC, and one for which no pigment assignment, based on characteristic cations or IR spectra, could be made but which exhibited a noteworthy Raman fluorescence.

Raman spectroscopy, FTIR spectroscopy, and SEM-EDX suggested that when organic colorants were suspected of remaining, their fading rates may have generally slowed

to below the detection limit of the microfader. Chemical analysis and color change analysis are fairly conclusive that vermilion and red lead are the principal pigments remaining vulnerable. However, there are so many unknowns that given the small number of caves examined, these current investigations can only be looking at the proverbial tip of the iceberg. Clearly more work is needed, preferably on samples large enough to support three replicate measurements each.

Conclusion

Color-fading analysis of samples from wall paintings in caves 217, 98, and 85 at the Mogao Grottoes showed a reasonable expectation that, except in one case, the organic pigments in the wall paintings were no longer at high risk for continued rapid fading. However, certain inorganic pigments already darkened from light exposure can be expected to continue this darkening trend. Thus there is no basis to assume that the wall paintings are light-inert, when half of the samples suggest or confirm otherwise.

A long-term monitoring program, responding to future use of the Mogao Grottoes, is recommended. It behooves the present caretakers of the site to embrace all future planning for artificial illumination in the caves with the spirit of preventive management.

Notes

- 1 The color space defined by the Commission Internationale de l'Éclairage is called CIELAB, where an L^* coordinate represents the lightness and darkness of the sample, a^* represents the red to green axis, and b^* represents the yellow to blue axis. From this location one is able to calculate a Euclidean distance relative to any other location, and this value of color difference is termed " ΔE ." The CIE defined and updated the color difference equation in 1994 (ΔE^*_{94}) and in 2000 (ΔE^*_{00}). Ideally, ΔE^*_{00} would have been the equation of choice, but under some conditions it can render slightly problematic results. For a more detailed description of color difference equations, see Berns, Billmeyer, and Saltzman 2000; Fairchild 2005. All figures in this paper are plotted as a change in ΔE^*_{94} over time of exposure.
- 2 Feller relates the story told by the Roman author Vitruvius of the notary Faberius who ordered his house on the Aventine to be painted with cinnabar. After only thirty days, the walls had become so dark and ugly that Faberius ordered them repainted with another pigment.

- 3 Feller assumed that the vermilion darkening reaction was caused by the solid-state transformation of α - Hg_2S (specific gravity 7.71) to metacinnabar, α' - Hg_2S (specific gravity 8.18), but he remarked that he was unable to derive that from spectrophotometric techniques alone.
- 4 Some intra-paint layer chemical conversions seem to require higher humidity (and sodium chloride), azurite \rightarrow atacamite, and others, low humidity, lead (II, IV) oxide \rightarrow lead (IV) oxide.
- 5 This is indicated by increases in L^* , a^* , and b^* and not by the darkening and reduction in a^* for cinnabar.

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Origins of Moisture Affecting the Wall Paintings in Cave 85

Shin Maekawa, Liu Gang, Xue Ping, Guo Qinglin, and Hou Wenfang

Abstract: *The Dunhuang Academy has observed wall painting flaking and plaster detachment, sometimes followed by collapse of areas of plaster, in cave 85 and other caves of the Mogao Grottoes after major rainfall. A condition survey of cave 85 documented severely deteriorated areas in the deepest westernmost portion of the cave. Analysis of the earthen plaster and conglomerate bedrock revealed high concentrations of sodium and chloride and lesser amounts of other ions in the west wall. Laboratory tests on salts collected from the cave found that they began to absorb moisture from the air at 67 percent relative humidity. As part of the cave 85 wall painting conservation project an environmental investigation was undertaken to identify all possible origins of moisture that might result in dissolution, hydration, or deliquescence of salts in the rock, plaster and paintings, leading to soluble salt-activated deterioration.*

Open entrance doors allow rapid infiltration of outside air. This mechanism is believed to be the principal route for environmentally driven deterioration when the outside is humid. Based on this study, it is recommended that the entrance doors to cave 85 be kept closed and that visitors be restricted as much as possible during periods of high humidity in the summer months.

Cave temples at Mogao were carved into the conglomerate rock of the cliff that had been eroded by the Daquan River. The temples are carved into three or four tiers, and their sizes range from less than one cubic meter to more than several thousand cubic meters. Wall paintings were executed on double layers of mud-plaster, with a coarse base and fine finishing layers applied to the surface of the bedrock. Paintings in many caves on the base tier show similar deterioration,

principally on their west walls. It has been noted that areas of painted plaster tend to fall after prolonged rain.

Cave 85, a large cave (floor area approx. 106 m²/volume 850 m³) dating from the Tang dynasty, was flooded before the Daquan River was confined to its present channel. Prior to the installation of the concrete facade and aluminum entrance doors in the 1960s, the antechamber and the entrance to the corridor leading to the cave's main chamber were exposed to the elements at all times. From 1986 to 1998 entrance doors to the cave were left open during visiting hours to accommodate tours. However, in May 1998 the cave was closed to visitation for investigation into causes of the deterioration of the wall paintings and for its conservation.

A condition survey of the wall paintings recorded major losses and deterioration on the west walls and western portions of both north and south walls (Piqué, Wong, and Su Bomin, this volume). Damage ranges from flaking of paint layers to the separation or detachment of the plaster from the bedrock. Chemical analysis of both plasters and bedrock conglomerate (Schilling et al., this volume) revealed that both the plaster layer and the conglomerate contain deliquescent salts. The principal species were sodium, chloride, and lesser amounts of sulfate (primarily at the base of the cave where flooding had occurred).

Sodium chloride deliquesces above 75 percent over a range of temperatures. Although sodium sulfate deliquesces at a higher relative humidity (97–98%), it hydrates and swells at 65 to 71 percent.

The moisture equilibrium isotherm of a plaster sample taken from a fallen ceiling fragment was measured. The sample absorbed the moisture almost linearly with the relative humidity increase up to 75 percent. Moisture amounted

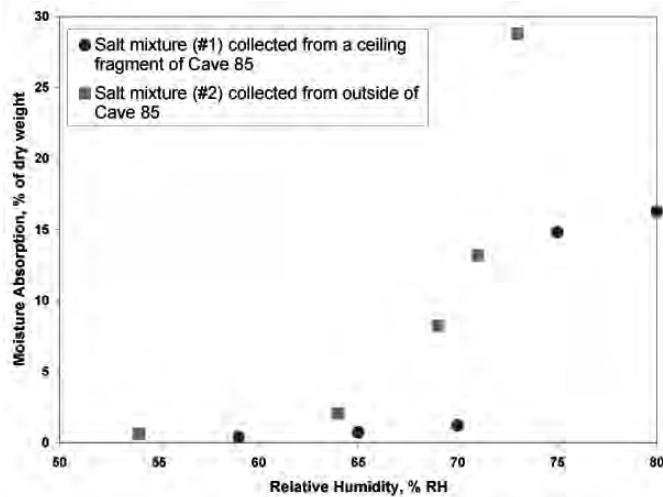


FIGURE 1 Moisture absorption of salt mixtures collected from the Mogao Grottoes.

to 1 percent of the dry weight and 1.5 percent during the desorption process in a 75 percent relative humidity (RH) environment. However, above 75 percent RH, absorbed moisture increased markedly. At 96 percent RH, nearly 4 percent moisture by weight was taken up by the plaster. This moisture uptake was similar to that of typical clay.

Figure 1 shows weight changes of salt samples extracted from a ceiling fragment of cave 85 that fell during an extended rain event in 1995 (salt mixture #1) and salt samples extracted from exposed conglomerate at the site (salt mixture #2) in various RH environments. Salt mixture #1 deliquesced between 70 and 75 percent RH, and its saturated solution produced a 74 percent RH environment. Salt mixture #2, on the other hand, started to hydrate at 67 percent RH and continued to increase its weight until the RH reached about 70 percent; a major weight increase occurred at about 71 percent RH.

Consequently, a five-year investigative environmental study was undertaken in cave 85 to identify sources of moisture that could cause the deterioration of the wall paintings by elevating the relative humidity to higher than 67 percent on and in the wall paintings.

Investigative Environmental Study of Cave 85

The investigative environmental study of cave 85 (1998–2002) began with a survey of possible sources for both liquid and vapor water. The following sources were considered.

For liquid water entering the cave:

- Surface infiltration of rainwater;
- Subterranean migration of the irrigation water from the poplar trees about 15 meters from the cave entrance; and
- Capillary rise of groundwater through the bedrock (see Tanimoto et al., this volume).

For water vapor entering the cave:

- Humid outside air in summer;
- Moisture generated by visitors; and
- Moisture transported through the bedrock by capillarity, groundwater, or rainwater channeled into fissures in proximity to the cliff face.

Environmental Monitoring

Environmental monitoring equipment was installed to identify moisture from the possible sources identified above. The following monitoring activities provided data for the environmental assessment.

Climate at the Site. In September 1989 an autonomous weather station had been installed on the cliff top of the site to record the climate. Since that time air temperature, relative humidity, solar radiation, wind direction and speed, rainfall, and ground surface temperature have been recorded. More than fifteen years of data were used for the analysis of meteorological data.

Climate in Cave 85. In December 1992 the Dunhuang Academy installed a temperature and relative humidity sensor in cave 85, along with adjacent caves, as part of its own investigation into the deterioration of wall paintings in the caves. This data set was also used for this study. Monitoring continued to April 1998 and then was expanded to measure spatial variations in the cave with the placement of a set of the temperature, relative humidity, and surface temperature sensors at four locations: the northwest and southwest corners, the center of the cave, and outside the entrance door.

Environmental Conditions in the Bedrock Conglomerate. Countless numbers of fissures are present along the cliff face. These fissures run parallel to the cliff face and generally perpendicular to the ground (Englekirk 1997). They may collect rainwater during events of extended or heavy rainfall. The collected moisture could eventually evaporate into the environment through cave walls, transporting salts in the process and enriching the surface.

Capillary rise of groundwater was considered not to affect the wall paintings due to the depth of the groundwater.

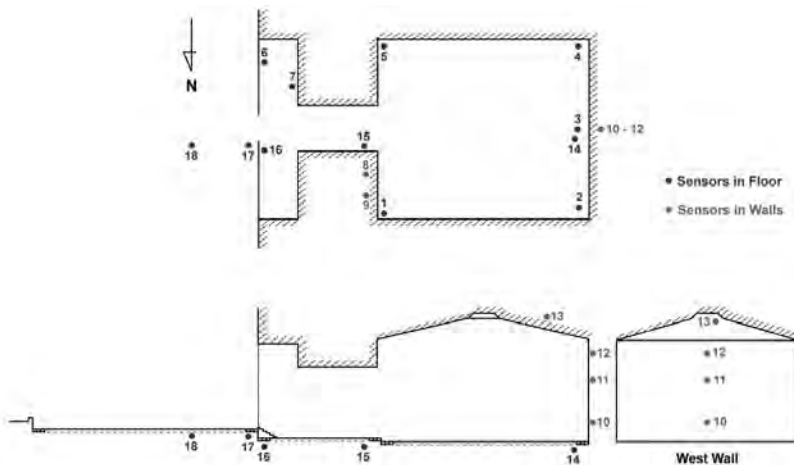


FIGURE 2 Locations of structural relative humidity and temperature sensors placed in the bedrock conglomerate of cave 85.

An evaluation of an existing water well confirmed the 30-meter depth of the groundwater at the site. However, several structural temperature and relative humidity sensors were placed in walls, as well as in the floor of the cave (fig. 2) to investigate variations of the environment in the bedrock conglomerate in cave 85 at 10-centimeter and 30-centimeter depths.

Moisture Seepage from Flood Irrigation in Cultivated Area. Mature poplar trees grow along the east face of the cliff to shade the walkway and protect the cave entrance

from wind-driven sand and are regularly flood irrigated. The cultivated area is especially close (~15 m) to the caves' entrances near cave 85. Therefore, while events of flood irrigation by the Dunhuang Academy were being recorded, moisture was monitored for seepage using structural temperature and relative humidity sensors at a 10-centimeter depth in the sand under the concrete tiles covering the area between the trees and the entrance of the cave.

Environments in Other Caves. The microclimate in several other caves was monitored: (1) those regularly visited as well as those closed to visitors, to isolate the impact of visitation on the caves' climate; (2) those at different tiers of the cliff, to understand the climatic variations due to vertical distance from ground level; and (3) those with low infiltration rates of outside air.

Findings and Discussion

Climate at the Site

The Mogao Grottoes are located in an arid environment. The site's annual rainfall average over a long period is about 25 millimeters; however, the amount varies greatly, for example, from 50 millimeters in 2000 to 3 millimeters in 2004. Rain events occur mainly in the three summer months—June, July, and August—when most visitors come to the site. Normally a rain event lasts less than a few hours; however, between 1989 and 2005 several sustained rain events occurred. One of them, in July 1996, lasted for nearly two weeks and resulted in the damage previously referred to. Temperature ranges from the -20°C in late January to the 40°C in mid-August. Daily averages range from -12°C in December and January to 20°C to 35°C in June, July, and August with a typical daily variation of 10°C to 15°C . Relative humidity normally remained between 10 and 30 percent throughout the year, although it is somewhat higher in winter. Occasional snow and rain events (normally less than a few days) cause spikes of elevated relative humidity (70–90%) as weather systems pass through the area (fig. 3).

Typical daily wind measures 4 to 7 meters per second from the south; however, occasional gusts reach 20 meters per second at the site during a sandstorm. The wind direction shifts daily from southeast to northwest at midday.

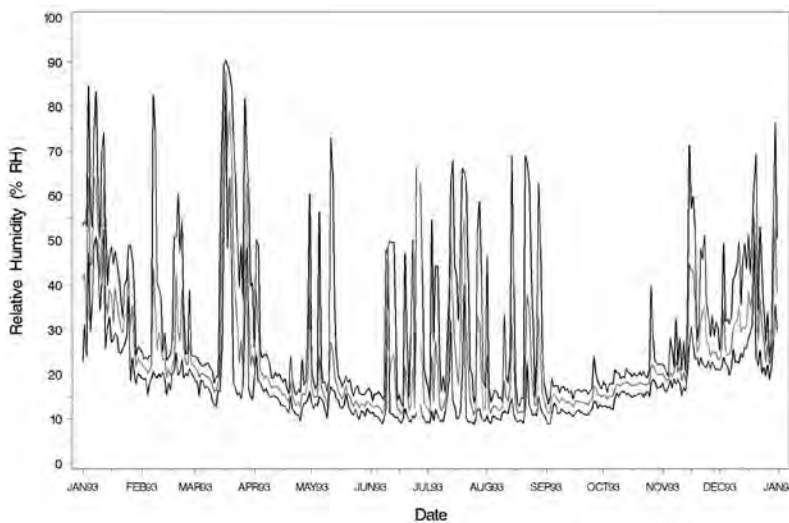


FIGURE 3 Typical annual variation of relative humidity at the Mogao Grottoes. This example is from 1993.

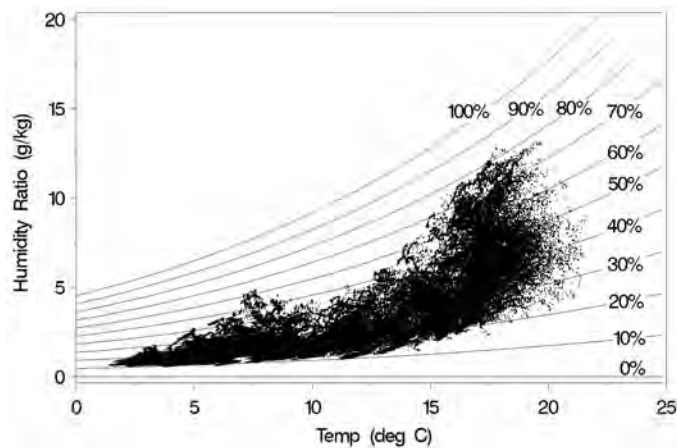


FIGURE 4 Temperature and relative humidity in cave 85 between 1993 and April 1998 (the cave was open to self-guided tours during operational hours), plotted on a psychrometric chart. Each dot represents a 15-minute (temperature and relative humidity) measurement. Conditions of higher than 75 percent RH were recorded annually during the period.

Climate of Cave 85

Since May 1998 cave 85 has been closed to visitors and the entrance doors have been kept closed most of the time. Over a five-year period the temperature ranged from -1.5°C in February to 20°C in September. Daily variations were only from 1.5°C in summer to less than 0.8°C in winter.

The relative humidity in the cave ranged from less than 10 percent in January and February to percentages in the 40s to 70s in June, July, and August. During rain events in summer months, the relative humidity increased from percentages in the 40s to the 70s, depending on the length and intensity of the event.

Prior to May 1998, when cave 85 was open to visitation (with entrance doors left open during hours of operation), the cave's climate variations were amplified. Figure 4 shows the temperature and relative humidity in cave 85 between January 1993 and April 1998 plotted on a psychrometric chart. Temperature ranged from 2°C to 22°C , and relative humidity annually reached 75 to 80 percent during rain events in summer. This may have been due either to moisture released by visitors in the cave or to infiltration of humid outside air through the open entry doors, or to both.

As expected, we documented the largest effects of the outside climate in areas closer to the cave's entrance, such as the antechamber, corridors, and east walls. The west wall was

least affected by the outside climate; thus it was the coldest in summer and warmest in winter. The temperature difference between the center of the cave and the west wall was approximately 1.5°C ; therefore, the west wall had 5 to 6 percent higher surface relative humidity than the center in late summer. However, the temperature difference between the east and west walls was typically less than 0.5°C ; this difference translated to less than 2 percent RH. Therefore, these climate variations between cave walls were minimal throughout the main chamber, eliminating the possibility that climate variations within the cave contribute to deterioration of the wall paintings.

Climate in Sealed Caves and Different Tiers

Caves 29, 310, and 423, which are ground-, middle-, and upper-tier caves, respectively, were monitored with their entrance doors closed and no visitation allowed. We observed that the climate inside these caves became warmer, and therefore drier, with increasing elevation on the cliff. The entrance doors to these caves were then covered with a plastic sheet to further reduce the infiltration of the outside air into the cave environment. The sealed environments were even drier in summer but more humid in winter than the cave environments with doors closed but not sealed. These facts indicate that the caves could be kept drier in summer by effectively reducing infiltration of humid outside air during rain events.

Irrigation Water

The grove of trees in front of the caves was flood irrigated daily during the summer months. We found wet sand under the concrete floor tiles of the walkway between the garden and the entrance to cave 85. Sensor readings verified the wet condition (100% RH with humidity ratio > 17 g/kg during the summer irrigation period). However, liquid water was confined to shallow depths, and its intrusion into the cave stopped just inside the entrance. Moisture dissipated before reaching the entrance of the corridor connecting to the east walls of the main chamber of the cave. Furthermore, the sand under the floor tiles between the garden and the cave dried out during the nonirrigation periods in fall and winter.

The Dunhuang Academy stopped flood irrigation in 2000 and replaced it with a drip system, which used a fraction of the water. Since that time, neither high humidity nor water has been found in the sand, even outside the cave's entrance. Furthermore, relative humidity levels in the cave floor remained the same as before. These findings further

indicate that irrigation water was not a source of moisture in the caves.

Rainwater through Fissures in Bedrock Conglomerate

To identify any relationship between variations in subsurface relative and absolute humidity and rain events, we compared both the short-term and long-term values in the west wall and in other parts of cave 85. Although we found significant seasonal variations of moisture at depths of both 10 centimeters and 30 centimeters that corresponded to climate changes at the site, there was no evidence that rain events affected wall humidity. This seemed to eliminate the possibility that fissures in the bedrock conglomerate act as rainwater reservoirs that feed moisture directly to cave surfaces. It was not possible, however, to survey the rock body comprehensively, as only areas where loss of painted surface had occurred could be used to insert probes.

High Humidity of the Bedrock Conglomerate in the West Wall

At 10 centimeters depth in the bedrock conglomerate of the west wall of cave 85, the temperature and relative humidity varied from 25 to 30 percent RH at 4–6°C in winter to 50 to 60 percent RH at 17–18°C in summer (fig. 5). These results indicate that the outside humidity strongly influences the shallow skin of the cave’s walls. At 30 centimeters depth, annual variations in temperature were similar to those at 10 centimeters depth; however, the relative humidity was higher and more stable (RH was 50% in winter and 60% in

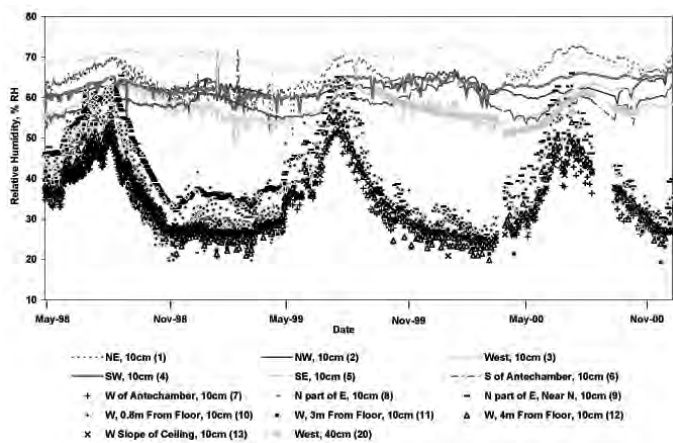


FIGURE 5 Annual variations of relative humidity in the bedrock of cave 85 between May 1998 and November 2000.

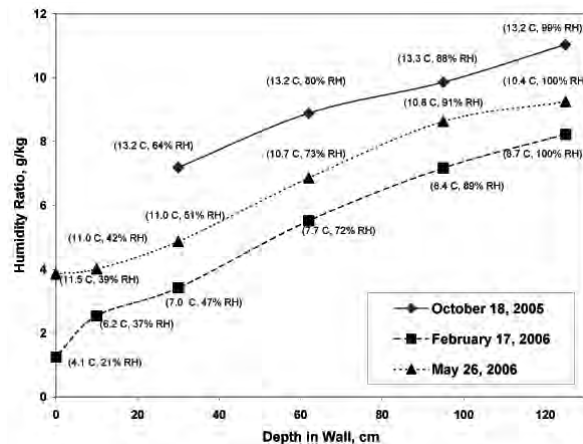


FIGURE 6 Humidity ratio of the bedrock in the west wall of cave 98 at various depths and seasons. Temperature and relative humidity are also indicated at each measured location.

summer). At 10 centimeters depth in the floor, the relative humidity was stable and varied from 65 percent in winter to 70 percent in summer. At the 30-centimeter depth in the floor near the west wall, the condition was least affected by the site’s climate at all measured locations: throughout the year, the temperature remained at approximately 10°C, and RH remained constant at approximately 85 percent.

Subsequent to the monitoring discussed above, in October 2005 three holes approximately 125 centimeters deep and 10 centimeters in diameter were cored into cave 98’s west wall, where all painting had been lost, and the adjacent floor to investigate the movement of moisture and salts. This cave is architecturally similar and has deterioration similar to that of cave 85. A series of structural temperature and RH sensors were inserted and isolated from each other and the chamber at depths of 125, 85, 60, 30, and 10 centimeters. At depths of about 100 centimeters the hole maintained 100 percent RH throughout the year. In both the wall and the floor, the relative humidity was above 75 percent at depths greater than about 60 centimeters; therefore, the NaCl in the bedrock should remain in solution at depths greater than 60 centimeters (fig. 6).

The moisture content gradient along the depth indicates that the moisture has been transported from deep bedrock to near the cave’s surface. However, the amount of moisture is small (due to the presence of large and numerous pebbles). The moisture transport rate is small in comparison to the high moisture removal rate at the surface (due to the

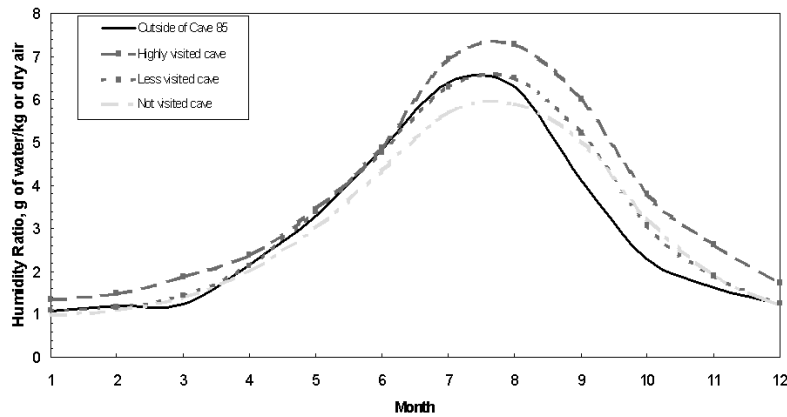


FIGURE 7 Monthly averages of humidity ratio at the site and inside highly visited, less visited, and not visited caves of the Mogao Grottoes.

normally dry cave air), so that less than 65 percent RH conditions were found at less than 30 centimeters depth throughout the year. Higher relative humidity in cave 85 as well as in the cave's floor at depths of 30 centimeters in comparison to that in cave walls indicated that concrete floor tiles, 5 centimeters thick, act as vapor retarders, reducing the moisture transfer from the floor to the cave air.

Impact of Visitors

In 1991 environmental monitoring was conducted in caves 323 and 335, which are architecturally similar to cave 85, though smaller. In the summer months approximately 5 percent higher relative humidity occurred in cave 323 (open) than in cave 335 (closed) (Maekawa et al. 1997).

Recent monitoring in cave 29, a medium-size (estimated volume 260 m³) and highly visited cave, included wall humidity measurements (fig. 7). Similar results were obtained: wall humidity rose by 5 percent (from 45% to 50% RH) during the peak months, a clear indication of the impact that visitors have on moisture in the air inside the cave.

Infiltration of Outside Air

Air infiltration rates of several large caves (55, 61, 98, 100, and 108) on the ground tier and architecturally similar to cave 85 were measured. These caves had periods of time when their entrance doors were left either open or closed. These caves were chosen because it was not possible to measure air infiltration rates in cave 85 due to the scaffolding that had been installed during the project. With the entrance doors

open, air infiltration rates were between 2 and 4 air changes per hour (ACH) and an order of magnitude lower (0.1–0.5 ACH) with the doors closed.

Air infiltration is mainly driven by the temperature difference between the cave interior and the outside: the larger the difference, the higher the infiltration rate. During the summer, temperatures in these caves were between 16°C and 20°C, and the outside temperature was normally in the 30s°C during the day and in the 20s°C during the night. However, the outdoor temperature dropped to the low 20s°C during rain events, producing smaller temperature differences with the cave interior temperatures and hence lower infiltration rates. After 4 to 5 air changes conditions inside and outside a cave will essentially be the same. This could occur in one to three hours, depending on the ACH of the particular cave. During summer rain events, the outside moisture content of the air increases from the normal value of 6.5 grams per kilogram to 12 to 13 grams per kilogram. With a cave infiltration rate of 2 to 4 changes per hour, the infiltration of humid outside air is equivalent to having 80 to 160 visitors in cave 85 during rainy days. This finding suggests that the moisture levels in the caves are predominantly influenced by the outside climate and the cave's air infiltration rate.

Documented Damage during a Prolonged Rain Event

Figure 8 is a combined plot of the rainfall, relative humidity of outside air, and relative humidity inside cave 85 between July 15 and August 2, 1996. On July 20, before a measurable rainfall event, the humidity in the cave rose from 42 to 75 percent RH, the humidity outside. This indicated that the outside humid air had infiltrated into the cave. Although the outside relative humidity decreased to less than 65 percent for the three days following the rainfall, the cave's interior relative humidity did not (the outside humidity remained high). Then a continuous rain event on July 26–27 coupled with the humid outside condition preceding and following the rain kept the cave's relative humidity above 75 percent. Although the total precipitation was low, the rainy condition continued until July 31.

After nearly eleven continuous days of above 65 percent RH in the cave, and with relative humidity continuously above 75 percent inside the cave for six of those days, the humid inside air had hydrated or deliquesced salts in the bedrock

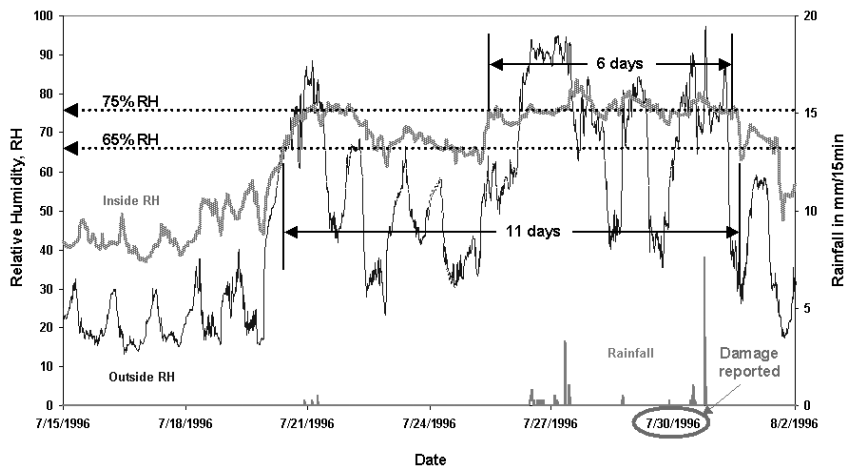


FIGURE 8 Combined plot of the rainfall, relative humidity of outside air, and relative humidity in cave 85 between July 15 and August 2, 1996. Bars extending from the baseline indicate the measured amount of rainfall for fifteen-minute periods. The Dunhuang Academy reported damage to the wall paintings in the cave on July 30.

conglomerate. This caused a large ceiling fragment of painted plaster to collapse, which was reported on July 30. The event demonstrates a relationship between extended humid or rain events, with prolonged elevated humidity above 65 percent RH, and damage to the cave walls.

Conclusions and Recommendations

External climate data from the Mogao Grottoes, as well as microclimate data from cave 85 supplemented with environmental monitoring from other caves, were used to identify sources of moisture in the cave that could cause the relative humidity to reach higher than 67 percent at the critical value established in the laboratory on extracted salts. We reached the following conclusions that apply specifically to cave 85 but more generally also to other caves. Climate variations occur seasonally and diurnally in the caves; however, they are below the critical relative humidity at which salt-related deterioration occurs. Flood irrigation of the trees in front of the caves does not affect the wall paintings.

- Saturated conditions (100% RH) exist in the bedrock deeper than 100 centimeters. This gradient can provide a transport mechanism for salts from the bedrock to the west wall of caves. (See Agnew et al., this volume, on mechanisms of deterioration.)
- Moisture released by many visitors increases humidity in caves; however, this is significant only in smaller caves.
- Caves with salt-related deterioration should remain closed to visitation on rainy summer days. If visitors are allowed into such caves, their numbers should be limited to minimize the amount of moisture they release.
- Real-time monitoring of relative humidity in susceptible caves should be considered.

Acknowledgments

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Development and Testing of the Grouting and Soluble-Salts Reduction Treatments of Cave 85 Wall Paintings

Stephen Rickerby, Lisa Shekede, Fan Zaixuan, Tang Wei, Qiao Hai, Yang Jinjian, and Francesca Piqué

Abstract: *A major problem affecting the Mogao caves is the separation and occasional collapse of their painted earthen plasters from the conglomerate rock support. Formulating a treatment for this problem was a key focus of the collaborative project of the Dunhuang Academy and the Getty Conservation Institute to conserve the paintings of cave 85. Plaster separation in cave 85 was widespread and severe, affecting most of its west end, including, critically, the ceiling slopes, and substantial other areas. Injection grouting is used in wall painting conservation to reestablish adhesion between separated plaster and its support. Little research has been done on paintings on earthen plasters. In cave 85 compatibility was of paramount importance, and local earth was considered the only appropriate binder material. To counter the drawbacks of its density and shrinkage, the selection and proportions of the other grout components, in particular the filler materials, were crucial. These were adopted following characterization of a range of potential materials with regard to their appropriateness and functionality. Grout mixtures were put through laboratory trials, to assess performance characteristics and working properties. Additional testing included artificial aging. The use of an earthen grout with water as a fluidizer in cave 85 meant that treatment would activate soluble ions in the heavily salt-contaminated plaster. It was therefore necessary to develop a salt absorption system as a corollary to grouting. Testing was conducted on lightweight, highly absorbent materials, to be used in conjunction with the presses placed against the plaster to support it during and after grouting. Laboratory tests and in situ trials were devised to assess absorption and desorption of salts. The development and testing of these remedial interventions resulted in a comprehensive treatment methodology that has since been applied throughout cave 85.*

Among the most prevalent and serious problems in the painted Buddhist caves of Mogao is the separation and collapse of their earthen plasters from the conglomerate rock support.¹ These failures typically stem from defects in the creation of the paintings, such as shrinkage of the plasters on drying and their inadequate bonding to the poor-quality conglomerate. In many caves, salt-related deterioration further complicates these inherent faults. Past remedial treatments have included pinning with anchors and, in extreme cases, the detachment and transfer of paintings. Pinning has tended to concentrate stresses on already weakened plaster layers, leading ultimately to their further damage or complete loss (fig. 1).² The second approach is also discredited, based on recognition of the irreparable harm inflicted by detachment and transfer.³

Injection grouting—introducing an adhesive material with bulking properties—is now the treatment of choice for tackling the critical issue of plaster separation (Griffin 2004: 23). Grouting research, mostly related to lime-based wall paintings, spans the past two decades.⁴ A systematic methodology for development and testing has only been quite recently established, however, through the work of Griffin (1997, 2004) at the Courtauld Institute.⁵ For earthen wall paintings—both more numerous and more difficult to treat than lime-based paintings, owing to their greater susceptibility to a wider range of deterioration phenomena—grouting research is surprisingly rare. Further work by Griffin (1999) provides the only substantive basis for the testing and development of fully compatible earthen grouts.

The collaborative project to conserve cave 85 at Mogao was an opportunity to design a compatible earthen grout for large-scale application. Cave 85 is a large late Tang cave



FIGURE 1 Previous attempts to address the problem of plaster separation in cave 85 have included pinning with rods and anchors. These have tended to concentrate stresses on already weakened plaster layers, leading to further damage and loss. Photo: Stephen Rickerby

with over 350 square meters of painting. At the start of the project in 1998, much of its earthen plaster was dangerously separating from the conglomerate rock. Areas of separation were large, in terms of both area and volume, and were concentrated at the west end of the cave, most critically on the ceiling slopes. Due to the weight of the thick plaster, cracking and bulging were typical, and sudden collapses had occurred. Widespread soluble-salt contamination of the rock and plaster compounded these conditions.⁶ The treatment mandate was therefore exceptionally challenging, requiring not only the development and testing of an appropriate grout but also the corollary development of an efficient salt-reduction system.

The Nature of Grouting: Constraints and Issues

Assessment before, during, and after grouting is severely constrained by the concealed nature of both the problem and its treatment, and lack of control is a fundamental drawback (Griffin 1997: 3). Much depends on the judgment and experience of the conservator.⁷ At sites such as Mogao, where plaster

separation and collapse are major problems, many liters of grout may need to be injected.⁸ This scale of treatment far surpasses almost all other conservation interventions in terms of the quantity of materials applied. Grouting, moreover, is completely irreversible: a set grout is a nonextractable part of a wall painting. Since no one in conservation can claim to be fully satisfied with current knowledge of the condition and deterioration of wall paintings, or their long-term interaction with added conservation materials, it is essential that these formidable treatment constraints—imprecision, invasiveness and irreversibility—be fully recognized in grout design.

Compatibility

Because a grout becomes an integral part of a wall painting and retreatment is extremely difficult, it must be composed of materials that are as similar as possible to those of the original plaster, so that original and added materials behave similarly. Differences in application and function between an original plaster and a grout mean that compatibility must be qualified. Earthen plasters include aggregates and organic fibers, added to counter physical problems such as shrinkage. The properties imparted by these materials, however, are only partly measurable. Moreover, the same materials cannot be automatically transferred to a grout mixture, which needs to be easily injected, and substitute materials may need to be added to enhance grout performance.

Because physical compatibility with the original materials must be approximated, chemical compatibility is crucial. The clay fraction of an earthen plaster must be replicated in the set grout. However, the perceived drawbacks of earth, such as excessive shrinkage and low strength, have led to its avoidance as a grout binder.⁹ Instead, earthen wall paintings are routinely injected with unsuitable lime-based grouts;¹⁰ or, when earth is used, it is typically hybridized with synthetic adhesives, compromising its natural binding function. The development of a grout that relied entirely on earth as its binder—a principle first established and tested by Griffin (1999)—was adopted as a starting point on the cave 85 project.

Earthen Materials Analysis

The main components of an earthen grout and their functions and potential disadvantages are shown in table 1. To overcome the possible deficiencies, the mineralogical and clay-containing characteristics of the earth component must be known. With this data, an informed selection of the other material components can be made.

Table 1 Earthen Grout Components and Their Potential Disadvantages

Grout Component	Function	Potential Disadvantages
Binder earth	bind the solid components of the grout mixture	<ul style="list-style-type: none"> • high wet and dry densities • long drying time • high shrinkage
Fluidizer water	activate clay component	<ul style="list-style-type: none"> • damage to water-sensitive/soluble plasters and paint materials • activates salts
Filler(s)	<ul style="list-style-type: none"> • provide bulk and enhance internal cohesion • counter shrinkage • improve porosity and water vapor permeability • reduce density • improve viscosity (injectability) • increase drying rate 	<ul style="list-style-type: none"> • may compromise compatibility • may result in too low or too high strength
Additive(s)	modify grout properties further (optional)	<ul style="list-style-type: none"> • may compromise compatibility

Characterization tests performed on mud collected from the dry bed of the seasonal Daquan River, which passes in front of the Mogao Grottoes, and on plaster samples taken from cave 85 showed them to be mineralogically nearly identical (table 2).¹¹ The revealing difference is that the plaster contains about 35 percent more sand. It is likely that either the riverbed mud was adapted for use as a plaster by adding a sandy aggregate or another local soil source was used that already contained a sandy aggregate.

Based on the similarity of its properties to the original plaster, the riverbed mud was selected as the grout binder. The mud is characterized by its high silt content (71%), relatively

low swelling clays, and near-absence of sand. For earthen supports to function well, an equal distribution of silt, sand, and clay is desirable. Too much silt, for example, is neither a good binder nor an aggregate and produces a material prone to shrinkage and cracking. The sand in the original plaster reduced its silt component to about 45 percent and the clay component to about 19 percent, which was still sufficient to bind the plaster. For the grout, testing therefore focused on characterizing and selecting fillers that would, like the sandy aggregate and straw in the original plaster, modify its performance (counter shrinkage, provide internal cohesion, etc.) while also imparting necessary grouting properties.

Table 2 Earthen Materials Analysis

Particle-Size Distribution					
	sand (0.06–2 mm)	silt (0.002–0.06 mm)	clay (<0.002 mm)		
Riverbed mud	1%	71%	28%		
Cave 85 plaster	36%	45%	19%		
Cave 85 plaster (without added sand)	1%	69.5%	29.5%		
Mineralogy of Clay-Size Fraction					
	kaolin	illite	chlorite	smectite	mixed illite/smectite
Riverbed mud	—	50%	40%	—	10%
Cave 85 plaster	—	40%	30%	—	30%

Characterization of Fillers

Given the wide range of available filler materials, an informed preselection was made, predicated on the known deficiencies of the earth binder and on the modifying role of the other components in the original plaster.¹² In the original plaster, a high aggregate-to-binder ratio (4:1) and a significant amount of added straw helped to reduce undesirable shrinkage. The straw also added mechanical strength, countering the poor packing geometry of the rounded sandy aggregate. Unfortunately, neither straw nor substitute fibers are injectable. In the grout, the filler components therefore needed to improve on the particle-size distribution and morphology of the plaster aggregate. They also needed to have low wet and dry densities, as the condition of the paintings could not support excessive added weight.

These requirements were too demanding for one material alone, and at least two fillers were necessary. Pretrial selection was based on simple visual and microscopic characterization and on basic qualitative and semiquantitative laboratory tests. Parameters examined included particle size and morphology, wet and dry densities, amount and rate of water absorption and desorption, drying times after saturation, and material expansion and contraction. Chemical characteristics such as pH and soluble-ion content were also determined.

Earthen Grout Design and Testing: Performance Characteristics and Working Properties

The most consistent and comprehensive methodology for the development of grouts has been researched, tested, and established by Griffin (1997, 1999, 2004). Based on assessment of the performance characteristics and working properties of grout formulations, this approach underscored the development and testing of the cave 85 grout.

Performance characteristics relate to the long-term performance of the intervention and are most important because the stability of the wall painting depends on them (Griffin 1999: 11–12). For grouts, they include the following:

- minimal physical or chemical alteration of painting
- minimal volume change
- similar porosity to plaster
- similar water vapor permeability to plaster
- similar mechanical strength to plaster
- similar hygrothermal behavior to plaster
- no soluble ions
- good adhesion
- durability and chemical stability

- microbiological resistance
- low density
- retreatability (since grouting is irreversible)

Working properties are concerned with short-term behavior while a grout is still in a liquid state and include the following (Griffin 1999: 11):

- injectability
- viscosity
- tack (initial adhesion)
- reasonable setting time
- low toxicity

For the wall paintings of cave 85, two other working properties of the liquid grout were important:

- minimal water content
- slow water release

Quantitative and replicable laboratory trials, derived from national and international standards, have been established for assessing many of the performance characteristics.¹³ Because working properties are ephemeral, obtaining exact values is less important, and basic qualitative and semiquantitative tests have been designed or adopted for their assessment. Because working properties are also concerned with constraints imposed by the nature and condition of the specific wall painting, tests vary from case to case as well. For example, since the painted plaster in cave 85 is water-sensitive, simple tests were designed to compare and assess both the water content and the rate of water release of the earthen grout mixtures.¹⁴

Basic performance characteristics (e.g., linear shrinkage, density, and water vapor permeability) and working properties (e.g., wet density, drying time, water content, and rate of release) were evaluated initially. Grout mixtures that did not reach appropriate standards in these areas were omitted from further testing. Thus, although more than eighty grout formulations were tested, only a small proportion of these were subjected to the full range of testing, culminating in specific strength tests such as uniaxial compression, yield strength, Young's modulus, and modulus of rupture. The final components of the grout-development program involved a series of in situ tests and artificial aging trials.¹⁵

With compatibility a primary concern, it was essential to relate the specific values acquired from laboratory testing

to the nature of the original plaster. However, differences in application and function between an original plaster and an injected grout make comparison difficult. In addition, it is often not possible to obtain sufficient amounts of original plaster for comparable testing.

There are no clear-cut solutions to these problems, and approximation is unavoidable. For cave 85, a replica plaster was prepared as a comparative base. Its components—36 percent sand, 45 percent silt, 19 percent clay, and added straw—were derived from the results of the earthen materials analysis of original plaster samples (table 2). The replica plaster was then put through the same performance tests as the grout mixtures, to provide a set of comparative values.

Cave 85 Grout Formulation

The selected grout formulation is shown in table 3. Some of the key performance data for the grout and the replica plaster are shown in table 4. The largest component of the grout is inert glass microspheres. These are widely employed as lightweight fillers in conservation practice, and their usefulness as a grout component is well recognized.¹⁶ Being non-absorbent, they have the significant advantage over porous fillers of maintaining extremely low wet and dry densities. Their spherical morphology, regular surface texture, and extremely small particle size also promote good viscosity and injectability; and their lightness contributes to the suspension of other grout components in the fluid mixture. However, their spherical morphology contributes to poor

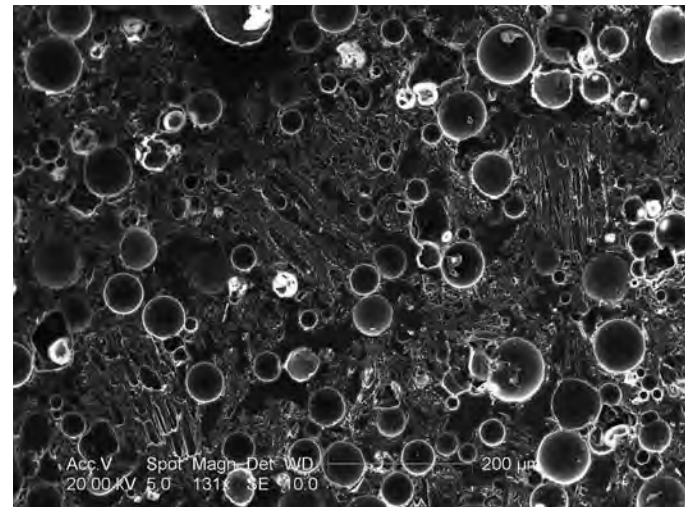


FIGURE 2 ESEM image of the formulated grout after setting, showing the distribution of the fillers in the earthen binder. The glass microspheres are clearly visible dispersed between the angular and variably sized pumice inclusions. Photo: Getty Conservation Institute

packing geometry, reducing internal cohesion: grout formulations tested with a higher proportion of glass microspheres were too weak.¹⁷ The pumice filler provides a counterbalance to this problem. Added as a relatively small proportion of the overall grout formulation, its variable and larger particle size and angular morphology favor internal cohesion (fig. 2). At the same time, the pumice has remarkably low

Table 3 Cave 85 Grout

Component	Material	Particle Size	Volume
Binder	washed and crushed riverbed mud	75 μm–0.6 mm	1
Filler 1	glass microspheres (Scotchlite K1*)	<75 μm	2
Filler 2	sieved pumice	75 μm–150 μm	1
Fluidizer	distilled water		0.66+
Additive	egg white (whisked)		5% (by volume of dry components)

Table 4 Key Performance Values

	Wet Weight (g)	Dry Weight (g)	Shrinkage (%)	Density (g/cm ³)	Water Vapor Permeability	Uniaxial Compression	3-Point Load (MPa)
Cave 85 grout	101	59.4	2.2	1.05	5×10^{-4}	1.168	0.456
Cave 85 replica plaster	124.6	86.5	2.4	1.72	4×10^{-4}	1.553	0.354

wet and dry densities compared to other angular fillers, such as sand.¹⁸

Adhesion is crucial. Two qualities are necessary: initial wet adhesion (tack) when the grout is injected and lasting adhesion once it has set. Synthetic adhesives have been added to earthen grouts to fulfill these demands, at risk of compromising the earth's natural binding function. Extensive research by Griffin, however, demonstrates the considerable adhesive and strengthening properties of egg white as a compatible protein additive, augmenting rather than substituting for clay binding properties.¹⁹ Egg white was therefore adopted for the cave 85 grout, whisked and folded into the mixture as a lightweight, air-entraining foam.²⁰ This also improves viscosity and injectability and prevents sedimentation. The egg white also makes up part of the fluidizer, allowing a reduced volume of water and restraining the rate of water release from the grout. Thus the egg component of the cave 85 grout is crucial for a variety of reasons.

Soluble-Salts Reduction

The use of an earthen grout with water as its fluidizer in cave 85 meant that treatment would dissolve soluble ions in the salt-contaminated plaster.²¹ Salts reduction was therefore required as an adjunct of grouting. Although salts reduction has a long history in conservation, usual techniques rely on the moisture supply and contact time of an applied (wet) poultice; research and practice are also mostly related to lime-based plasters.²² For cave 85, the moisture supply was instead water released from the grout. Patterns of moisture transfer and salt phase transitions in earthen plasters are poorly understood. However, aqueous reduction of salts, including treatment limitations and difficulties, has, in general, received considerable study, providing a basis for developing an approach for the particular issues in cave 85.²³

Testing focused on characterizing highly absorbent wipes that could be incorporated while dry into the presses placed against the plaster after grouting.²⁴ Efficient absorbency and low desorption were essential performance criteria; conformance and lightness were desirable working properties. Tests were devised to assess amounts and rates of moisture uptake and desorption by the wipes when placed against a wet substrate. Since in the case of aqueous extraction the time span for safe and effective absorption is known to be limited, it was anticipated that frequent replacement of the absorbent layers would be necessary to avoid harmful backward migration.²⁵

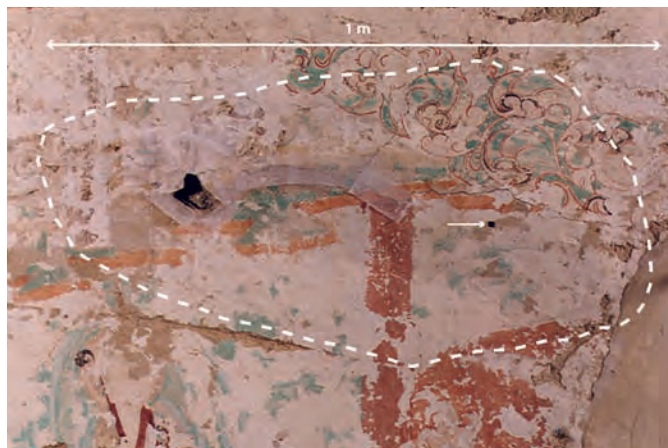


FIGURE 3 Grout Area 5 on the west wall of cave 85, showing the extent of a typical area of plaster separation. In the development of the soluble-salt reduction procedures, comparative microcore samples were taken *before* grouting and *after* grouting and salt-reduction treatment. The white arrow indicates the location of a *before grouting* microcore, taken in an area of unpainted plaster. The *after grouting* microcore would be taken adjacent to this, to minimize analytical error.

Verification by in situ trials was essential. Soluble-ion analysis of the removed absorbent materials was undertaken to evaluate extraction rates during the drying time of a grouted area. Maximum extraction occurred immediately after grouting, with a decline thereafter as the grouted plaster slowly dried.²⁶ To evaluate the redistribution of remaining ions in the wall painting, comparative microcore samples were taken before and after grouting. Potentially harmful salt accumulation at key internal interfaces—at junctures between the painting layers, the ground, the plasters, the deposited grout, and the conglomerate support—was a particular concern, and samples were therefore collected at depths corresponding to these strata. Results were variable, reflecting difficulties of sampling and interpreting data under extremely heterogeneous conditions.²⁷ Broadly, however, they pointed to a general lowering of soluble-ion levels in areas of grouting, particularly at key interfaces within the wall painting (figs. 3, 4).

Conclusion

Given the complexity of the conservation problems in cave 85, the development of the grouting and salts-reduction treatments was a substantial undertaking, which benefited

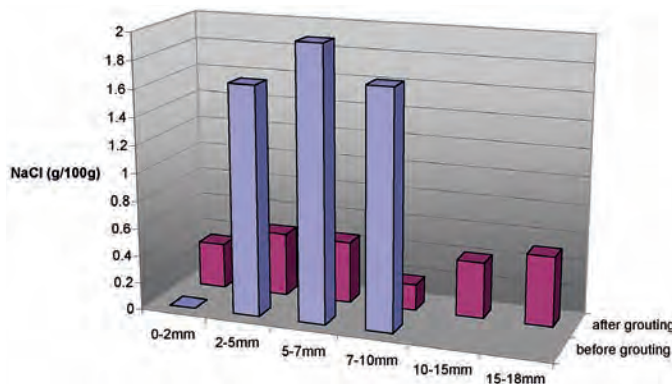


FIGURE 4 Soluble-ion (Cl⁻) results of microcores taken *before* and *after* grouting and soluble-salts reduction treatment for Grout Area 5 (also see fig. 3). The *before grouting* microcores attained an overall depth of 10 millimeters (mm) before reaching the void in the detached plaster; the result for the 0–2 mm increment is anomalous, probably due to loss of material during sampling. For the *after grouting* microcores, the 10–15 mm and 15–18 mm increments were taken through the injected grout, reaching back to the conglomerate rock. The results indicate a significant reduction in chloride levels after treatment.

from considerable previous research. In the context of much recent earthen materials conservation, the formulation of a grout that relied entirely on the clay fraction of its earth component for its binding function was a core accomplishment. In its physical and chemical properties, the grout is uniquely matched to the particular conditions and treatment constraints of cave 85. This also provides an important model for the way in which an intervention as difficult as grouting must be approached: particular circumstances of original technique, condition, and deterioration must be reflected in grout design.

Acknowledgments

The authors wish to acknowledge all members of the cave 85 project, whose individual and collective work contributed to the development of the grouting and salts-reduction treatments. We are fundamentally indebted to Sharon Cather, who, over the past decade, has significantly influenced the direction of grouting research.

Notes

- 1 The development and testing of the injection grouting and salts-reduction treatments of cave 85 were conducted at the Dunhuang Academy, Lanzhou University, and the Getty Conservation Institute from 1998 to 2002. Analytical procedures, data, and results are not reported in full in this paper but will be accessible from the Project Report Web site.
- 2 Although this problem has been little studied, see Leitner 2000 for research into the dynamics of structural failure associated with pinning painted plaster to suspended wooden ceilings.
- 3 For a recent discussion of the detrimental effects of wall painting detachment and transfer, see Brajer 2002.
- 4 See, e.g., Ferragni et al. 1984: 110–16; Botticelli et al. 1986: 177–79; Baglioni et al. 1997: 43–54; Barcellona et al. 1993: 637–43; Teutonico et al. 1994.
- 5 Building on Griffin's grouting research, a significant forerunner of the cave 85 grout was the design of a lime-based grout by Stephen Rickerby and Lisa Shekede, during the collaborative program of the Courtauld Institute and the Valletta Rehabilitation Project to conserve the late-sixteenth-century wall paintings by Filippo Paladini in the Chapel of the Grandmaster in the Magisterial Palace, Valletta, Malta, which was treated from 1998 to 2004 (publication forthcoming).
- 6 For a fuller discussion of the deterioration problems in cave 85, see Agnew, Maekawa, and Shuya Wei, this volume.
- 7 A range of nondestructive instrumental techniques have also been used for assessing plaster separation, including 3D laser scanning and modeling, ultrasonic pulse vibration and measurement, and infrared thermography. For examples, see Rickerby et al., on grout implementation, this volume.
- 8 Almost 300 liters of grout were injected in cave 85. The largest area of plaster separation was injected with 22 liters.
- 9 Griffin (1999: 57), however, found that earthen grouts shrank less than lime-based grouts, because they required lower water content to achieve the same consistency.
- 10 Inherently poor adhesion between lime- and earth-based materials has been noted by Griffin (1999: 13, 60) and Cather (2003: 169).
- 11 See note 1 above for further details.
- 12 Because fillers primarily alter the physical properties of a grout, they are usually selected for their chemical inertness. The possibility of using chemically reactive fillers in earthen grouts has not been explored. Materials such as calcite, silica, and ferric oxide, for example, have been shown to act as cementing agents in earth mixtures, forming chemical bridges between clay micelles that may reduce swelling (Foth 1990: 31).
- 13 See, e.g., Griffin 1999: App. D.

- 14 No testing standards have been specifically formulated for conservation grouts, and the wide range of national and international standards that exist have mostly been developed for cement-based mortars. Tests for performance characteristics and working properties carried out during the development of the cave 85 grout were based on those of Griffin (1997, 1999, 2004) and employed American Standards (ASTM) and Chinese Standards (CSTM). For full details, see note 1 above.
- 15 In situ trials included measuring the shear resistance of analogue panels grouted onto the rock conglomerate of the cave. Artificial aging of grouted plaster replicas, some doped with 2 percent NaCl, involved cycling these at 100 percent relative humidity for 48 hours, followed by their exposure to ambient relative humidity (ranging from approximately 20 to 40 percent) for 24 hours. See note 1 above for full details and results.
- 16 For a discussion of filler materials in conservation, including glass microspheres, see Smith 2000. Glass microspheres were used as a lightweight filler in the lime-based grout developed for the wall paintings in the Chapel of the Grandmaster in the Magisterial Palace, Valletta, Malta (see note 5 above).
- 17 Although SEM micrographs of glass microspheres show breakage of individual spheres, this does not occur on a sufficient scale to improve their overall packing geometry and promote better cohesion.
- 18 Pumice is also a natural pozzolana, though no pozzolanic reaction occurs in the cave 85 grout mixture due to the absence of calcium hydroxide (Ca(OH)₂).
- 19 Proteins are among the organic substances that react chemically with clays, one possible mechanism being the exchange of inorganic cations in the clay for organic ones; a further mechanism relates to the ability of amino acids to encourage clay flocculation (Griffin 1999: 21–22 and refs.). Amino acids are present in some quantity in egg white (Mills and White 1987: 76). Griffin found that egg white used as an additive in earthen grouts promoted tack and adhesion, increased plastic and liquid limits, and increased uniaxial compressive strength and modulus of rupture (Griffin 1999: 24–31, 35, 39–42, 44–45, 51–60, 63–65, 69).
- 20 Egg white also has a long tradition of use as an additive to lime plasters and mortars because of its adhesive properties (Sickels 1981: 27, 37), and it is still similarly employed by conservators in Austria (H. Leitner, pers. com.). Partly based on these precedents, it was also used in the lime-based grout to conserve the wall paintings in the Chapel of the Grandmaster in the Magisterial Palace, Valletta, Malta (see note 5 above). The preparation of the egg white in this grout in turn influenced its use in the development of the cave 85 grout.
- 21 Salt investigations indicate that the soluble-ion content in the plaster at the west end of the cave can be up to 4 percent (expressed in weight %) and that the most common ions are sodium and chloride. See Agnew, Maekawa, and Shuya Wei, this volume, for a fuller discussion of the salt contamination in cave 85.
- 22 An aqueous poultice removes salts from a wall painting in two stages: a *humidification* or *penetration* stage, whereby the poultice acts as a support for introducing water into the wall painting; and a *drying* stage, when the poultice provides a sacrificial evaporation zone into which salts migrate before being discarded (Tinzi 1994: 16, 18, 23). For a recent collection of papers on salt contamination of lime-based wall paintings and approaches to salts-reduction treatments, see Leitner, Laue, and Siedel 2003.
- 23 The main risks associated with salts-reduction treatments include the harmful redistribution of salts and preferential extraction of more soluble salts, leaving behind less soluble and potentially more damaging salts (Cather 2003: 169–70). For further discussion in relation to cave 85, see Rickerby et al., on grout implementation, this volume.
- 24 The materials tested were highly absorbent tissues, manufactured from absorbent cellulose fibers bonded to nonwoven polypropylene fabric. These were also tested impregnated with dried riverbed mud, to enhance their absorbency. For further details of the selected absorbent system, see Rickerby et al., on grout implementation, this volume.
- 25 During aqueous extraction, a concentration equilibrium is established between the filled capillaries of the substrate and those of the applied absorbent. At this point, backward migration may occur, due to greater capillary attraction of the substrate (see Grüner and Grassegger 1993). Thus while the absorbent materials tested for cave 85 were capable of absorbing large amounts of moisture, this potential was ultimately reversed when employed on a wet substrate.
- 26 For further discussion of the drying time of the absorbent presses in cave 85 and evaluation of salts reduction, see Rickerby et al., on grout implementation, this volume.
- 27 For the difficulties of salt sampling in terms of characterizing topographic and stratigraphic distribution, see Cather 2003: 168.

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Implementation of Grouting and Salts-Reduction Treatments of Cave 85 Wall Paintings

Stephen Rickerby, Lisa Shekede, Fan Zaixuan, Tang Wei, Qiao Hai, and Yang Jinjian

Abstract: *Because of extensive areas of earthen plaster detachment and the widespread presence of salts in the plaster and rock substrate, remedial treatment of cave 85 at the Mogao Grottoes was a singularly challenging task. The Dunhuang Academy and the Getty Conservation Institute devoted considerable resources to the development and testing of the principal remedial interventions: injection grouting and soluble-salts reduction.*

Injection grouting is an imprecise and high-risk intervention. Pretreatment assessment, treatment control, and posttreatment evaluation are all inhibited by the concealed voids between the rock substrate and the plaster. The reduction of soluble salts is also hazardous for the wall paintings, as it risks harmful redistribution of the salts. Since salt reduction and grouting had to be undertaken simultaneously in cave 85, the already difficult treatment became riskier and more complex.

A well-defined treatment methodology was therefore essential. Meticulous preparation of the grout in small quantities maintained quality control and ensured that the grout was used in its optimal working state. A protocol for in situ treatment was developed to determine delivery options, injection points, and the localized consolidation and/or temporary facings required. Considerable planning was dedicated to the design and dimensions of the presses placed against the plaster after treatment, since these had to simultaneously provide physical support and absorb both moisture from the grout and dissolved salts from the plaster. Postinjection monitoring extended over a three- to four-week drying period. Analytical support before and after grouting determined soluble-salts reduction in treated areas. Given the difficulty of the treatments, the competence of the conservator in terms of practical

skills and in interpreting diverse and complex wall painting phenomena was a key consideration.

The remedial treatment of the late Tang dynasty (618–906) wall paintings of cave 85 at Mogao was a singularly challenging undertaking. The cave exhibited widespread separation of its painted earthen plaster from the conglomerate rock support and high levels of salt contamination in both the rock and the plaster. This created an exceptionally vulnerable and complex situation, whose remedy was the aim of the cave 85 project, a collaborative effort of the Dunhuang Academy and the Getty Conservation Institute. In preparation to treat the cave, the two organizations devoted some five years to the development and testing of the principal remedial interventions—*injection grouting and soluble-salts reduction*—alongside other interdisciplinary studies that focused on diagnosis of the underlying deterioration issues.¹ This allocation of resources reflected the difficulty of this single conservation endeavor. From 2002 to 2005 the injection grouting and salts-reduction treatments were implemented throughout cave 85.

Challenges Posed by Cave 85

The significant constraints of both injection grouting and soluble-salts reduction are accentuated in the case of earthen plasters, such as those at Mogao. Since the cohesion of the plaster depends largely on its moisture content and since a high moisture content can lead to loss of cohesion and even failure, the risks of employing aqueous-based treatments are obvious. Dangers clearly increase when the plaster layers are thick, heavy, and severely cracked and



FIGURE 1 Detail of cave 85 showing where painted earthen plaster has separated and fallen away from the underlying conglomerate rock. A metal cross-brace was bolted into the rock by Dunhuang Academy conservators before the collapse but failed to prevent it. Photo: S. Rickerby

bulging, as was the case in cave 85. On the west wall, the part of the cave most affected, approximately 70 percent of the 57 square meters of plaster was separated from the rock. Huge risks were posed by the typically large size of individual areas of plaster separation, some extending over 1 to 2 square meters, with a gap between the plaster and the rock of up to 4 centimeters (fig. 1). The diverse painting materials of cave 85—the preparatory ground, pigments, organic colorants, and glazes—are also all extremely water-sensitive and in some cases water-soluble.

In addition to the failing and vulnerable original materials, there was the coincidence of high levels of salts in areas of major plaster separation, especially at the west end of the cave.² Moreover, Cave 85 had a recent history of repeated remedial intervention, including widespread consolidation on several occasions with a polyvinyl acetate (PVAC) and polyvinyl alcohol mixture, which had only exacerbated persistent deterioration problems.

Treatment Constraints and Issues

Since grouting is irreversible, the twofold emphasis of the development of this treatment was compatibility of materials and “retreatability.” And since the concern was to effect the structural rescue of the wall painting, the set grout and the earthen plaster had to function well together, possessing the same or similar performance characteristics.

To this end, a decision was made to establish, through analysis, a local soil source that was physically and chemically similar to the earth component of the cave 85 plaster and to use this as the principal binder of the formulated grout (see Rickerby et al., on development and testing, this volume).³

With earth as binder, water was required as the grout fluidizer. This meant that soluble salts in the plaster and rock would be mobilized as a result of moisture migration. Salts-reduction measures therefore had to be developed and implemented as a corollary of injection grouting.

Both injection grouting and salts reduction are fraught with imprecision and risk. In the case of injection grouting, the concealed nature of the plaster voids constrains pretreatment assessment, as well as full control of the intervention and its posttreatment evaluation.⁴ Despite this, the treatment was concerned with wall paintings at the point of collapse and, therefore, with fundamental issues of plaster instability. Not only was the intervention a precarious one, but the risks were largely unquantifiable.

The reduction of soluble salts is also hazardous for wall paintings, potentially resulting in the harmful redistribution of the salts (Cather 2003: 167–72). Modern conservation practice favors environmental control as the most effective means of mitigating the activation mechanisms that lead to salt-related deterioration of wall paintings (Sawdy 2003: 95). Although ongoing environmental control also underpinned the remedial interventions of cave 85, salt-reduction treatment was unavoidable. However, the aqueous reduction of salts has received considerable study, making this a viable intervention despite its well-documented limitations.⁵

Treatment Methodology

Given the problems of assessment before, during, and after grouting and salt reduction, in situ application of both treatments has traditionally depended on the experience and judgment of practicing conservators. One unfortunate consequence of this has been reliance on visual evidence of “success” rather than on analytical evaluation. The cave 85 project offered an opportunity to address this situation by establishing a well-defined treatment methodology that incorporated analytical surveillance of results.

Pretreatment Assessment

A rigorous assessment of areas of plaster separation—aided by graphic and photographic documentation and written logs—was undertaken prior to grouting. The location and



FIGURE 2 Cracks in the painted earthen plaster in cave 85. Photo: S. Rickerby

extent of the plaster voids to be filled were determined by visual inspection and simple acoustic methods.

Fundamental aspects of the nature and extent of the plaster separation were established. Particular concerns were the gap between the plaster and the rock conglomerate (whether the plaster was flat or bulging or both); the condition of the plaster; the age, extent, and configuration of plaster cracks (fig. 2); and the perimeter of the zone of plaster separation. Aspects of condition, such as areas of paint flaking and plaster decohesion, were also recorded in order to identify stabilization treatments required before grouting and to determine grout delivery options and appropriate injection points.

One example may illustrate the role of the conservator. An original cause of plaster separation in cave 85 is attributed to shrinkage of the earthen materials on drying. Historic cracks associated with this failure could typically be identifiable because paint is carried over them. If the original cracks remained unchanged and the paint undisturbed, this would signify relatively stable conditions. If additional newer cracks later developed, disturbing the paint, this could point to a renewed threat of collapse and to the need for grouting. Categorizing degrees of risk in either case is not straightforward, and making such distinctions in practice required considerable judgment. An awareness of

diverse original plastering and painting techniques, of complex deterioration mechanisms and their effects on present condition, and of difficult treatment procedures and their limitations was essential.

Grout Preparation

The selected grout formulation was a product of considerable refinement regarding proportions of components, range of particle sizes, and particle morphology. Earth was its principal binder, and the two main fillers—glass microspheres and sieved pumice—were carefully formulated to counter potential drawbacks such as shrinkage and weight. Egg white was also added, imparting additional adhesive and strengthening properties. Prior to its use in cave 85, the grout was tested extensively (for *performance characteristics* and *working properties*), and aging trials were performed and assessed (Rickerby et al., on development and testing, this volume).

To maintain quality control, consistent preparation of materials was required before they were combined. Reliable grout formulation was maintained by establishing a strict protocol for measuring and combining the wet and dry components. Small quantities were produced to ensure accuracy. Given the relatively fast initial setting of the grout, this protocol also ensured that the mixture was used in its optimal working state.

In Situ Preparations

The combined treatment procedures involved considerable logistical preparation and coordination. Determining the size of individual grouting areas was essential for determining the size of the presses that would be placed against the plaster after treatment. Since these presses not only provided physical support after grouting but also incorporated highly absorbent layers to contain moisture released from the grout, press dimensions had to anticipate lateral moisture movement by a generous margin.

Other in situ measures included preparing injection points and implementing stabilization measures, such as the application of **localized temporary facings**, **localized consolidation**, and the fixing of paint flakes. Where possible, existing holes in the plaster were used as entry points for catheters and needles; on occasion, new holes had to be drilled, and these were made through areas of paint loss (fig. 3).

Grouting

As with all other aspects of treatment in cave 85, grouting partly evolved in relation to practical experience and



FIGURE 3 A grout catheter placed in an insertion point that has been stabilized with a temporary facing. Photo: S. Rickerby

acquired judgment. With this experience, protocols were put in place for the preparation of grouting equipment and materials and the sequencing and optimizing of specific treatment procedures. However, each area to be treated had to be assessed individually, since conditions varied from one area to another.

Because of the risks, caution and restraint were essential. Usually four conservators were involved in the grouting of a single area: two preparing the grout and syringes, one delivering the grout, and the other manually checking and supporting the plaster (fig. 4). Since grouting is a team exercise, effective communication was key. Oversight was maintained by compiling treatment logs detailing the amount of injected grout and the quantities of added water required to fluidize the basic grout mixture in response to differing grouting situations.

Importantly, the purpose of grouting was not to fill all voids. Many large voids were only partly filled to avoid adding too much additional weight. In such cases, the aim of grouting was to break up the internal volume of the voids and to provide strategic “anchoring.” Nevertheless, some



(a)



(b)

FIGURE 4 Grouting was a team exercise. Dunhuang Academy conservators (a) prepare grout and syringes and (b) deliver grout while supporting the treated area. Photos: S. Rickerby

idea of the scale of grouting in cave 85 can be gauged by the amount of grout injected: a total of nearly 300 liters.

Soluble-Salts Reduction

To absorb and contain moisture released from the grout, carrying with it dissolved salts from the original plaster and rock, absorbent tissue layers were incorporated into the presses that were placed against the treated plaster (fig. 5).⁶ This absorbent system was selected after extensive testing. Its efficacy in practice was dependent on monitoring and timing and involved teamwork between the project conservators and the conservation scientists.

While the materials used in the presses were capable of absorbing large amounts of moisture, this process could be reversed in situ. It was therefore important to remove and replace the absorbent layers frequently (to avoid reabsorption of moisture and salts by the plaster).⁷ Although the responses of treated areas to the salts-reduction procedures differed markedly depending on original technique and condition, analytical tracking of soluble salts in the absorbent layers established broad absorption patterns.⁸ Maximum absorption occurred immediately after grouting, with a decline



FIGURE 5 A customized press placed against treated plaster for support and to absorb moisture released from the grout. Photo: S. Rickerby

thereafter as the grouted area slowly dried completely, typically over three to four weeks; in the final stages of drying, little salt was detected. Based on these findings, the absorbent layers were changed up to three times a day in the first few days after grouting, decreasing to twice a day for much of the remainder of the drying period. Only in the final stages of drying was it safe to leave the absorbent presses in place for longer periods.

It was also necessary to check that harmful salts had not become redistributed in the grouted plaster. This was done with microcore samples taken before and after grouting (in areas of unpainted plaster) to establish soluble-ion levels at key interfaces within the grouted wall painting stratigraphy.⁹ This level of analytical surveillance was a key component of treatment implementation, involving the conservation team in sample taking and evaluation of results.

Posttreatment Monitoring and Care

Posttreatment monitoring of the grouted areas was intensive, extending over the three- to four-week drying period. During this time, a daily regimen was established for changing the absorbent layers in the presses—from preparing the absorbent materials in the laboratory to changing them in situ—and logging and evaluating the frequency of changes. To monitor overall drying rates, an infrared thermometer was used to compare spot measurements of treated (damp) and adjacent untreated (dry) areas until equalized temperatures were reached.

Daily checking and care of grouted areas coincided with the press changes, both measures requiring an awareness of early signs of salt-related and other deterioration. To prevent salt crystallization on or immediately below the surface of the paintings, it was necessary that monitoring—and any minor remedial treatments, such as re-laying lifted paint flakes—be completed swiftly, so the absorbent presses could be replaced quickly to reestablish capillary continuity.

After complete drying of the grouted areas, posttreatment care continued in other forms. Surface salts still present posed immediate risks that could be partly remedied. An ultrasonic humidifier that projected a fine mist of heated water onto the surface of the treated areas was used to dissolve the salts, which were then removed by tamping with highly absorbent wipes (fig. 6).¹⁰ This approach provided considerable control, limiting the amount of moisture added. As with the salts-reduction procedures, these additional measures were monitored by tracking chloride ion levels in the used absorbent wipes and by sampling the plaster to check



FIGURE 6 An ultrasonic humidifier being used to dissolve surface salts on the treated area of a wall painting. Photo: S. Rickerby

salt redistribution patterns. Results indicated that the treatment was capable of reducing surface salts without causing their adverse redistribution.

Other Remedial Interventions

Other treatments were carried out in cave 85, such as the fixing of flaking paint, localized consolidation of powdering plaster and/or paint, and new repairs to cracks and losses in the original plaster. Although these treatments were less extensive and less complex than the injection grouting and salts-reduction interventions, they nevertheless shared the same overall treatment methodology, which emphasized compatibility between original and added materials.

Furthermore, the earth and PVAC mixture used in previous repairs was removed and replaced with an earthen repair mixture with a composition based on materials analysis of the original plaster.¹¹ Analysis indicated that animal glue was used as an original plaster sealant, and gelatin was therefore selected as a compatible substitute to use as both a localized paint fixative and a plaster consolidant.¹² Prior to their use in cave 85, all additional treatment materials underwent extensive testing and assessment, including tests of performance characteristics and working proper-

ties, both in the laboratory and in situ; artificial aging trials were also performed.¹³

Conclusion

Until remarkably recently, it was customary conservation practice to detach wall paintings from their original support when loss of adhesion threatened their survival. Their remounting on artificial supports was then seen as a rational treatment solution to correct problems of deterioration. Recognition of the irreparable harm inflicted by these actions—both to the wall paintings and to the places they once occupied—and their failure to halt subsequent deterioration of the detached paintings have almost brought these practices to a halt. This fundamental change came about through the development, and acceptance, of injection grouting as a practical treatment alternative. That acceptance has been slow, and unnecessary detachment of wall paintings persists.

In this context, the practice of simultaneous injection grouting and soluble-salts reduction in cave 85 was a significant achievement. While much attention has been given recently to grout research and development, few other conservation projects have implemented compatible earthen grouting on such a major scale as this one carried out at Mogao.¹⁴

It is important, however, to appreciate fully the nature of the major treatment interventions undertaken in cave 85. Considered in isolation, neither is a panacea: injection grouting addresses a deterioration crisis, not its causes; and salts-reduction procedures cannot be viewed as a means of solving salt-related deterioration. It is also generally recognized that these treatments are imprecise and usually highly interventive. Because they are applied to wall paintings in conditions of advanced deterioration, both treatments are inherently risky, often in unpredictable ways.

Nevertheless, both interventions were required in cave 85, where they also had to be implemented on a large scale. Treatment therefore relied on a prior program of intensive testing and development and on analytical backup during implementation. The collaborative—and overlapping—roles of the conservator and the conservation scientist were key to this process. Remedial treatment was also only undertaken in a wider context of environmental investigation and diagnosis of the principal deterioration problems (Agnew, Maekawa, and Shuya Wei, this volume). Given the essentially limitless supply of salt in the painted plaster, long-term

conservation in cave 85 is ultimately dependent on localized control of the activation mechanisms of salt deterioration, through appropriate environmental intervention.

Acknowledgments

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Notes

- 1 For the development and testing of the injection grouting and salts-reduction treatments of cave 85, see Rickerby et al., this volume. Analytical procedures, data, and results from the Mogao Cave 85 Project Report will be forthcoming on the Getty Web site (www.getty.edu). For discussion of other areas of diagnosis and research related to the cave 85 project, see Agnew, Maekawa, and Shuya Wei; Maekawa et al.; and Schilling et al., this volume.
- 2 See Agnew, Maekawa, and Shuya Wei, this volume, for a discussion of the salt contamination in cave 85.
- 3 Particle-size distribution and characterization tests performed on samples of original plaster taken from cave 85 indicated that it was composed of 36% sand and 64% riverbed mud, with added straw. For more details of the earthen materials analysis carried out for the cave 85 project, see Rickerby et al., this volume.
- 4 Although manual acoustic methods remain the norm for detecting, recording, and, to some extent, qualifying the risks posed by plaster voids in wall paintings, various nondestructive instrumental techniques have also been used, including 3D laser scanning and modeling, for documenting spatial deformations (see, e.g., Casciu, Centauro, and Chimenti 2000); ultrasonic pulse vibration and measurement (see, e.g., Gosálbez et al. 2006); and infrared thermography (see, e.g., Grinzato et al. 1994).
- 5 For a recent collection of papers on the problems of salt contamination of wall paintings and approaches to salts-reduction treatments, see Leitner, Laue, and Siedel 2003. For a bibliography of previous literature on the desalination of porous materials, see Vergès-Belmin 2003.
- 6 The presses had a lightweight wood backing with polyurethane foam padding to provide firm but cushioned support to grouted areas of plaster. Over the foam padding were placed two layers of absorbent tissue, manufactured from paper-pulp fibers bonded to nonwoven polypropylene fabric (Kimberley Clark Wypall X60°). The absorbent tissue nearest the back of the press was also impregnated with dried, local riverbed mud, which acted as an additional means of holding absorbed moisture. On top of the tissue layers, lens tissue was incorporated as an intervention layer at the interface with the wall painting. Presses were applied against the plaster with the aid of custom-made press guns sprung from adjustable frames attached to the scaffolding.
- 7 During aqueous extraction of salts from a wall painting, equilibrium is reached between the concentration in the wall and that in the applied absorbent material. At this point, the applied absorbent will not absorb more salt, and backward diffusion into the plaster may occur. For these reasons, effective salt reduction is usually a repeated action. For fuller discussion, see Grüner and Grassegger 1993.
- 8 Since salt investigations indicated that sodium chloride is the major salt species present in cave 85, monitoring of salt levels in the absorbent layers used in the presses, and in the original plaster before and after treatment, was carried out with a chloride ion electrode on aqueous extracts. For a fuller discussion of the salt contamination in cave 85, see Agnew, Maekawa, and Shuya Wei, this volume.
- 9 Effective reduction of salts from a porous structure presumes that there is capillary continuity. Since wall paintings are typically composed of multiple layers, breaks between these strata are not uncommon, and disruptions occur in the capillary pore structure. During salts reduction, salt may crystallize at these interior breaks, resulting in salt concentrations at key interfaces of the wall painting. For a fuller discussion of the redistribution of salts, see Tinzl 1994: 68; Cather 2003.
- 10 The ultrasonic humidifier was a Preservation Pencil®, and the mist was heated to 50°C. The absorbent tissue wipes (paper-pulp fibers bonded to nonwoven polypropylene fabric) were manufactured by Kimberley Clark (Kimberley Clark KayDry EX-L®).
- 11 The earthen repair mixture was composed of 36% sand and 64% riverbed mud, with added straw. See also note 3 above.
- 12 See Schilling et al., this volume, for analysis of the animal glue sealant. Gelatin was used as a localized paint fixative or plaster consolidant in concentrations varying from 1 to 2%, depending on variable treatment circumstances and conditions.
- 13 For full details, see the Mogao Cave 85 Project Report, forthcoming on the Getty Web site (www.getty.edu).

14 Most of the conservation literature on grouts is primarily concerned with its laboratory-based development and testing (see, e.g., Ferragni et al. 1984; Botticelli et al. 1986; Baglioni et al. 1997; Barcellona et al. 1993). A significant precedent for the cave 85 project was the collaborative project of the Courtauld Institute of Art (University of London) and the Valletta Rehabilitation Project to conserve the late-sixteenth-century frescoes by Filippo Paladini in the Chapel of the Grandmaster, Magisterial Palace, Valletta (Malta), undertaken from 1998 to 2004. Based on grouting research at the Courtauld Institute (Griffin 1999, 2004), the Valletta project also focused on the development of a compatible grout (lime-based), followed by its large-scale implementation.

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Materials and Suppliers

Absorbent tissue and wipes:

Kimberley Clark Wypall X60®
Kimberley Clark KayDry EX-L®

Ultrasonic humidifier:

Preservation Pencil®
Preservation Equipment Ltd.
Vinces Road
Norfolk IP22 4HQ, England

A Rapid Means of Measuring Residual Salt after Grouting and Poulticing Wall Paintings

Chen Gangquan, Michael R. Schilling, Li Yanfei, Joy Mazurek, Yu Zhongren, and Lisa Shekede

Abstract: A nondestructive, semiquantitative spot test method was developed to determine chloride ion concentration on the surface of wall paintings in cave 85. Water in the grout used in the conservation project in the cave brought salts to the surface. The poulticing technique used with grouting reduced the surface salts and prevented crystallization, but a test was needed to provide a quick, reproducible method of determining residual salt on areas that had been grouted. The technique also had application in evaluating the effectiveness of the Preservation Pencil in further reducing surface salt in the same areas. The test comprises application of wet paper to the surface, followed by measurement of the chloride ion absorbed by the paper using a specific ion electrode. As a means of systematically mapping chloride, the technique has application both prior to and after interventions that mobilize soluble salts.

Hygroscopic Salt Redistribution and Removal in Poulticing

Localized separation of the painted plaster layer from the rock wall in cave 85, a condition classified as detachment, was a serious problem that required conservation intervention. Detachment was remedied by injecting grouting material into the void space between the plaster and the rock wall to readhere the plaster (Li Zuixiong 2005). Though effective, grouting had one significant drawback: mobilization and subsequent redistribution of hygroscopic salts, which consist largely of sodium chloride, that were present up to 6 percent by weight in the plaster layer (Li Zuixiong 2005; Schilling et al., this volume).

To address this concern, a poulticing procedure was developed that reduced the salt content of the paint and

plaster layers (Li Zuixiong 2005; Rickerby et al., “Testing and Development,” this volume). After poulticing, the salt content in the wall paintings was further reduced through the use of a Preservation Pencil (fig. 1), an ultrasonic humidifier manufactured by Preservation Equipment Ltd., England. By misting the wall paintings with water vapor directed from the nozzle of the device and blotting the paintings immediately with cotton paper, a portion of the salts could be removed safely from the painted surfaces (fig. 2).

The overall extent of reduction in the salt content of the plaster surface by poulticing could be estimated by a spot test developed specifically for the cave 85 project. In the



FIGURE 1 The Preservation Pencil.



FIGURE 2 Salts being removed with the Preservation Pencil.

spot test method, a **prewetted and standardized size of absorbent chromatography paper** was applied to the surface of the wall painting for a specified amount of time, then removed and immersed in deionized water. The concentration of chloride ion in the water was then measured by a chloride-specific ion electrode.

Spot Test Procedure

A single layer of chromatography paper (Grade 81-24) was cut into strips 1 centimeter by 2 centimeters (approximately 40 mg in weight and 1 mm in thickness). The paper strip was placed into distilled water using a fine-point tweezers and removed after five seconds. Excess water was removed by touching the paper strip to the container wall. The average weight of water in the saturated paper was 160 milligrams \pm 2 percent relative standard deviation (based on twenty-seven replicate measurements). The wetted strip was applied to the surface of a prefabricated clay coupon that contained 6 percent by weight of salt (Chen Gangquan et al. 2005), carefully avoiding pockets of air. It was determined that the paper should be removed after forty seconds, by which time a maximum of 60 milligrams of water will have entered the plaster coupon and penetrated to a depth of 2 millimeters. The paper strips were then put into plastic tubes that contained exactly 2 milliliters of deionized water, and after six hours the chloride ion concentration was measured using a chloride-specific ion electrode (Thermo Orion Model 290 meter and



FIGURE 3 Prewetted paper strip applied to a wall painting in cave 85.

Thermo Orion 9617BN chloride electrode, Orion Research Company, Boston, MA).

Calibration of the Spot Test Method

Developing a means to calibrate the spot test procedure was one of the most important aspects of this research. Plaster coupons fabricated with known quantities of salt would seem to be ideal candidates for calibration standards, although their porosity, texture, and water-uptake behavior do not match the properties of the original plaster layers in cave 85. Instead, the wealth of information obtained from the plaster microcore survey (Schilling et al., this volume) made it possible to calibrate the spot test with respect to the actual in situ salt concentrations. The spot test method was used on the west wall of cave 85 in areas where the painted surface had already been lost but where the integrity of the plaster surface was intact (fig. 3). After completion of the spot test measurements, **plaster microcore samples were taken adjacent to the spot test area in locations where no paint was present. The plaster microcores were approximately 5 millimeters in diameter and 2 millimeters deep.**

Based on the test results, a **calibration curve was constructed** by plotting the chloride ion concentration from the spot tests versus the plaster microcore samples (fig. 4). The relationship can be expressed by the equation

$$Y = 6.27X + 0.1005,$$

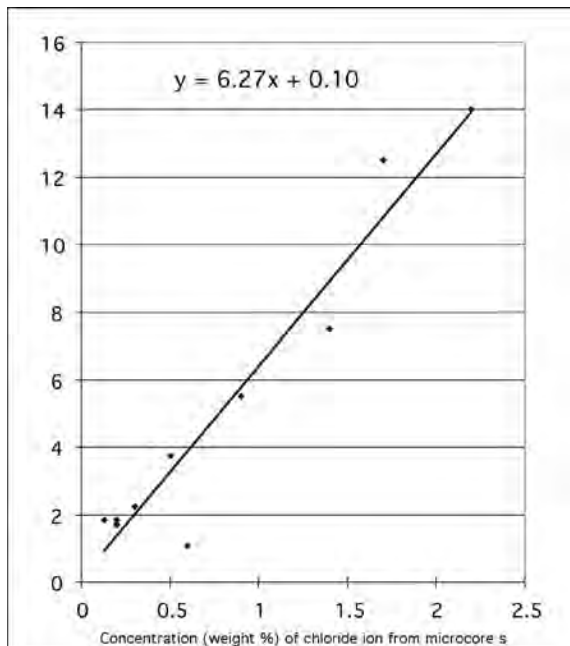


FIGURE 4 Relationship between chloride ion concentration in spot tests and plaster microcores.

where *Y* is the chloride ion concentration in parts per million (ppm) from the spot tests, and *X* is the chloride ion concentration in weight percent from the plaster microcores. A linear curve fitted to the data had a correlation coefficient, *r*, of 0.9633. Thus, with this equation, the approximate chloride ion concentration in the plaster layer of the wall paintings in cave 85 may be measured using the spot test procedure.

Application of the Spot Test Method to Grouted Plaster in Cave 85

The spot test method was used to assess the results of poulticing on the west wall in cave 85. Tables 1–4 list chloride ion concentrations for various types of plaster: untreated (ungROUTED) plaster (table 1), grouted plaster poulticed with X60 cotton paper (table 2), grouted plaster poulticed with X60 cotton paper and treated with the Preservation Pencil (table 3), and ungrouted plaster treated with the Preservation Pencil (table 4). Table 5 summarizes the results from the previous tables, and figure 5 illustrates the mean data from table 5. The test results indicate that after grouting the moisture from the grout redistributes hygroscopic salts within the plaster layer and enriches them at the surface.

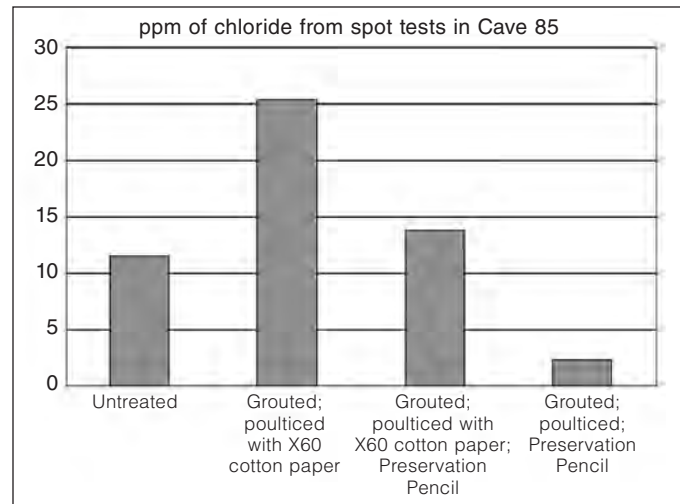


FIGURE 5 Summary of results from tables 1–5.

Table 1 Spot Test Results at UngROUTED Areas

#	Sample Location	ppm Cl ⁻
1	60cm from south wall, 138cm from floor	19
2	105cm from south wall, 200cm from floor	34
3	144cm from south wall, 200cm from floor	31
4	206cm from south wall, 200cm from floor	8
5	210cm from south wall, 180cm from floor	8
6	278cm from south wall, 168cm from floor	7
7	286cm from south wall, 200cm from floor	5
8	330cm from south wall, 198cm from floor	19
9	360cm from south wall, 182cm from floor	11
10	450cm from south wall, 140cm from floor	8
11	460cm from south wall, 170cm from floor	7
12	375cm from north wall, 150cm from floor	6
13	340cm from north wall, 200cm from floor	10
14	250cm from north wall, 135cm from floor	7
15	280cm from north wall, 200cm from floor	9
16	200cm from north wall, 123cm from floor	10
17	190cm from north wall, 202cm from floor	17
18	330cm from north wall, 175cm from upper frame	8
19	335cm from north wall, 165cm from upper frame	8
20	245cm from north wall, 150cm from upper frame	8
21	240cm from north wall, 148cm from upper frame	6
22	45cm from south wall, 75cm from top of west wall	8
		11.5 (mean)

Table 2 Spot Test Results at Grouted Areas Poulitced with X60 Cotton Paper

#	Sample Location	ppm Cl ⁻
23	70cm from south wall, 200cm from floor	8
24	115cm from south wall, 125cm from floor	5
25	148cm from south wall, 175cm from floor	17
26	210cm from south wall, 120cm from floor	25
27	230cm from south wall, 190cm from floor	47
28	270cm from south wall, 130cm from floor	5
29	300cm from south wall, 198cm from floor	166
30	330cm from south wall, 135cm from floor	6
31	355cm from south wall, 200cm from floor	3
32	355cm from south wall, 145cm from floor	7
33	470cm from south wall, 180cm from floor	5
34	505cm from south wall, 185cm from floor	8
35	545cm from south wall, 190cm from floor	10
36	320cm from north wall, 130cm from floor	21
37	250cm from north wall, 200cm from floor	10
38	240cm from north wall, 163cm from floor	10
39	220cm from north wall, 168cm from floor	11
40	160cm from north wall, 146cm from floor	12
41	160cm from north wall, 190cm from floor	7
42	85cm from north wall, 145cm from floor	10
43	88cm from north wall, 200cm from floor	8
44	45cm from north wall, 180cm from floor	14
45	10cm from south wall, 155cm from upper frame	143
46	45cm from south wall, 176cm from upper frame	49
		25.3 (mean)

Table 3 Spot Test Results at Grouted Areas Poulitced with X60 Cotton Paper and Treated with the Preservation Pencil

#	Sample Location	ppm Cl ⁻
47	210cm from south wall, 165cm from upper frame	12
48	165cm from south wall, 135cm from upper frame	19
49	210cm from south wall, 112cm from upper frame	9
50	235cm from south wall, 120cm from upper frame	68
51	295cm from south wall, 130cm from upper frame	8
52	325cm from south wall, 60cm from upper frame	7
53	380cm from south wall, 35cm from upper frame	9
54	400cm from south wall, 37cm from upper frame	4
55	420cm from south wall, 26cm from upper frame	5
56	435cm from south wall, 12cm from upper frame	5
57	395cm from north wall, 120cm from upper frame	7
58	340cm from north wall, 78cm from upper frame	5
59	310cm from north wall, 145cm from upper frame	5
60	250cm from north wall, 124cm from upper frame	10
61	225cm from north wall, 45cm from upper frame	8
62	235cm from north wall, 170cm from upper frame	10
63	164cm from north wall, 135cm from upper frame	10
64	145cm from north wall, 30cm from upper frame	42
65	88cm from north wall, 126cm from upper frame	42
66	165cm from south wall, 20cm from top of west wall	7
67	220cm from south wall, 22cm from top of west wall	13
68	175cm from south wall, 56cm from top of west wall	5
69	230cm from south wall, 90cm from top of west wall	5
		13.7 (mean)

Table 4 Spot Test Results at UngROUTED Areas Treated with the Preservation Pencil

#	Sample Location	ppm Cl ⁻
70	90cm from south wall, 40cm from upper frame	12
71	130cm from south wall, 48cm from upper frame	3
72	210cm from south wall, 65cm from upper frame	2
73	245cm from south wall, 75cm from upper frame	2
74	270cm from south wall, 80cm from upper frame	2
75	320cm from south wall, 76cm from upper frame	2
76	430cm from north wall, 50cm from upper frame	2
77	405cm from north wall, 80cm from upper frame	None
78	300cm from north wall, 35cm from upper frame	1
79	300cm from north wall, 70cm from ceiling	1
80	415cm from south wall, 60cm from ceiling	2
81	378cm from south wall, 70cm from ceiling	1
82	390cm from south wall, 115cm from ceiling	5
83	430cm from south wall, 125cm from ceiling	1
84	410cm from north wall, 120cm from ceiling	2
85	375cm from north wall, 130cm from ceiling	1
86	156cm from north wall, 95cm from ceiling	1
87	132cm from north wall, 98cm from ceiling	2
		2.3 (mean)

Poulticing with X60 cotton paper immediately after grouting reduces the salt content somewhat, although after poulticing the salt content remains roughly twice that of ungrouted areas. Treatment with the Preservation Pencil reduces the chloride content by 10 ppm, which is equivalent to 1.6 percent of chloride ion in the plaster layer, or 80 percent of the salt content of ungrouted plaster. Thus the Preservation Pencil was an integral part of the salt reduction process.

One limitation of the spot test method is that extremely friable plasters cannot be handled safely with the adsorbent paper. Moreover, moisture from the prewetted paper strips will carry salts deeper into the plaster layer, thereby reducing their concentration at the surface. However, if the process is standardized and conducted reproducibly, the calibration curve adequately compensates for many procedural variables.

Table 5 Summary and Results of Spot Tests in Cave 85: Chloride Ion Concentrations (in ppm) from Tables 1–4

	Untreated	Grouted & Poulticed, No Pencil	Grouted & Poulticed, with Pencil	UngROUTED, with Pencil
	19	8	12	12
	34	5	19	3
	31	17	9	2
	8	25	68	2
	8	47	8	2
	7	5	7	2
	5	166	9	2
	19	6	4	Not detected
	11	3	5	1
	8	7	5	1
	7	5	7	2
	6	8	5	1
	10	10	5	5
	7	21	10	1
	9	10	8	2
	10	10	10	1
	17	11	10	1
	8	12	42	2
	8	7	42	
	8	10	7	
	6	8	13	
	8	14	5	
		143	5	
		49		
Statistics				
<i>n</i>	22	24	23	18
Mean	11.5	25.3	13.7	2.3
% RSD	8	42	16	3

Conclusion

Hygroscopic salts present in painted earthen plasters are redistributed by aqueous grouting mixtures, which enriches them at the plaster surface and enhances the potential for damage. Poulting with paper, followed by treatment with the Preservation Pencil, greatly reduced the salt content at the plaster surface, as demonstrated by measurement data from a chloride ion spot test developed in the cave 85 project. The spot test was shown to be a rapid, inexpensive, and minimally invasive means of surveying the hygroscopic salt content of earthen renders.

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The Information Management System for the Cave 85 Project

Lorinda Wong, Francesca Piqué, Wang Xiaowei, and Xu Shuqing

Abstract: *This paper describes the information management system for the conservation of wall paintings project in cave 85. The information management system was created as a dynamic database of all information generated from the start of the project in 1997 through to its completion in 2005. Given the complexities of the deterioration mechanisms found in cave 85, the project required an interdisciplinary approach with joint investigation by conservation, documentation, analytical, and environmental teams. With a project of this scope, scale, and duration, new data were constantly being generated and existing data were continuously evolving. Over the course of the eight-year project each team produced significant quantities of data. The problem of managing the continuous flow of new information and maintaining control over the existing body of data, to allow access of information between project teams, was solved by establishing a data protocol system. This was a simple system for receiving, storing, and retrieving information that was managed by an information manager through whom all information flowed. In addition to organizing and storing information, the information management system facilitated the integration and synthesis of information between project teams. In particular, the integration of environmental, analytical, and conservation data was essential in establishing the deterioration mechanisms of the wall paintings that were critical for designing effective and appropriate treatment interventions and preventive conservation measures. This enabled informed decision making to guide the scope and management of the project. Lessons gained from the management of this large body of data have had wider application for the conservation of other caves at the Mogao Grottoes and at similar projects of this scale.*

Information management is integral to every aspect of the conservation process (see Piqué, Wong, and Su Bomin, this volume). Information management for the cave 85 project encompasses the collection, organization, storage, retrieval, integration, manipulation, and presentation of data. The eight-year project involved specialists from many fields: wall painting conservators, documentation specialists, photographers, historians, analytical chemists, and environmental scientists, among others. Copious information was generated in each of these areas.

With so much information being generated and multiple users involved on several continents and with data being produced in Chinese and English, the challenge was to establish a system that would work across disciplines while facilitating access by team members. Information management for the cave 85 project was therefore not a static endeavor focused only on organizing and storing information; rather it facilitated the integration, analysis, and use of data between teams essential in making educated decisions on how to preserve this important site and to move the project forward.

Problems

The cave 85 project data in electronic form consist of over 50 gigabytes of text, data, photographic, and graphic files. The files are in a number of different formats, including Microsoft® Word, Excel, and PowerPoint documents, Autodesk® AutoCAD drawings, Adobe® InDesign, Photoshop and Illustrator files, and thousands of digital images in RAW, TIFF, and JPEG format. The amount of information has steadily increased throughout the project, with a dramatic rise starting in 2003 with the transition from film to digital photography.

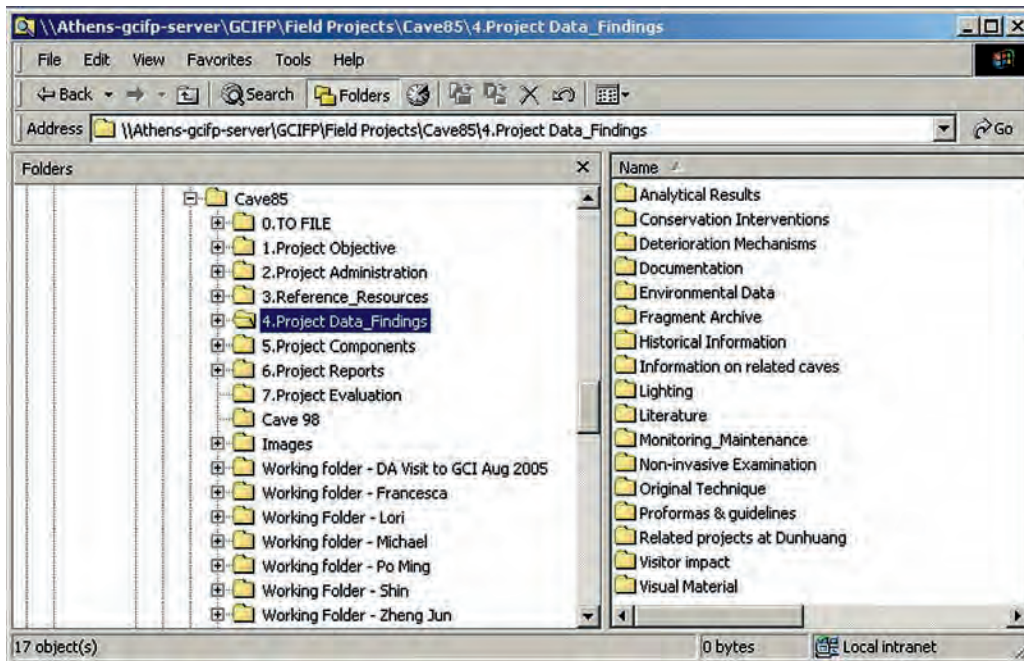


FIGURE 1 File organizational structure for the cave 85 project.

In a multiyear project of this nature, with many team members working in different locations, it became increasingly difficult and time-consuming to locate and retrieve relevant files. The lack of standardized file naming exacerbated the problem, as did the lack of centralized storage of files and an agreed-on file organizational structure. Files were often kept on personal computers, inaccessible to other team members. Multiple versions of a single file were generated without indication of when it was modified or by whom. These circumstances combined with inadequate communication between project team members led to wasted time and inefficiency.

Solutions

The decision to focus attention on information management came midway through the project. A protocol for receiving, storing, and sharing information was established; key to its implementation was the appointment of an information manager through whom all information would flow.

For cave 85, the information manager worked with project team members on the following tasks:

- *Data collection.* Receiving and monitoring data from project team members.
- *File naming.* Naming or renaming files following an agreed-on convention (including a brief

description of the content, metadata on the author, creation date, and file type; e.g., MOG.85.S04.EW.ToolMarks.FP.d.jpg includes the following information: Mogao Grottoes, Cave 85, Spring 2004 Field Campaign, East Wall, Tool Marks, Francesca Piqué, Digital image capture, jpg format).

- *Storage.* Storing files in their appropriate place on a shared folder and not on personal computers (the shared folder is a secure, networked location that allows access to all project members and is regularly backed up) following an agreed-on file organizational structure (fig. 1).
- *Data sharing.* Communicating receipt and availability of project information to team members, including the creation of a parallel database and the identification of an information manager at the Dunhuang Academy to allow for the exchange of critical documents.
- *Retrieval.* Locating files and helping direct team members to relevant information.
- *Maintenance.* Maintaining and reorganizing the shared folder and keeping information current.

The system required participation of the team and continuous attention and maintenance and relied on human accuracy.

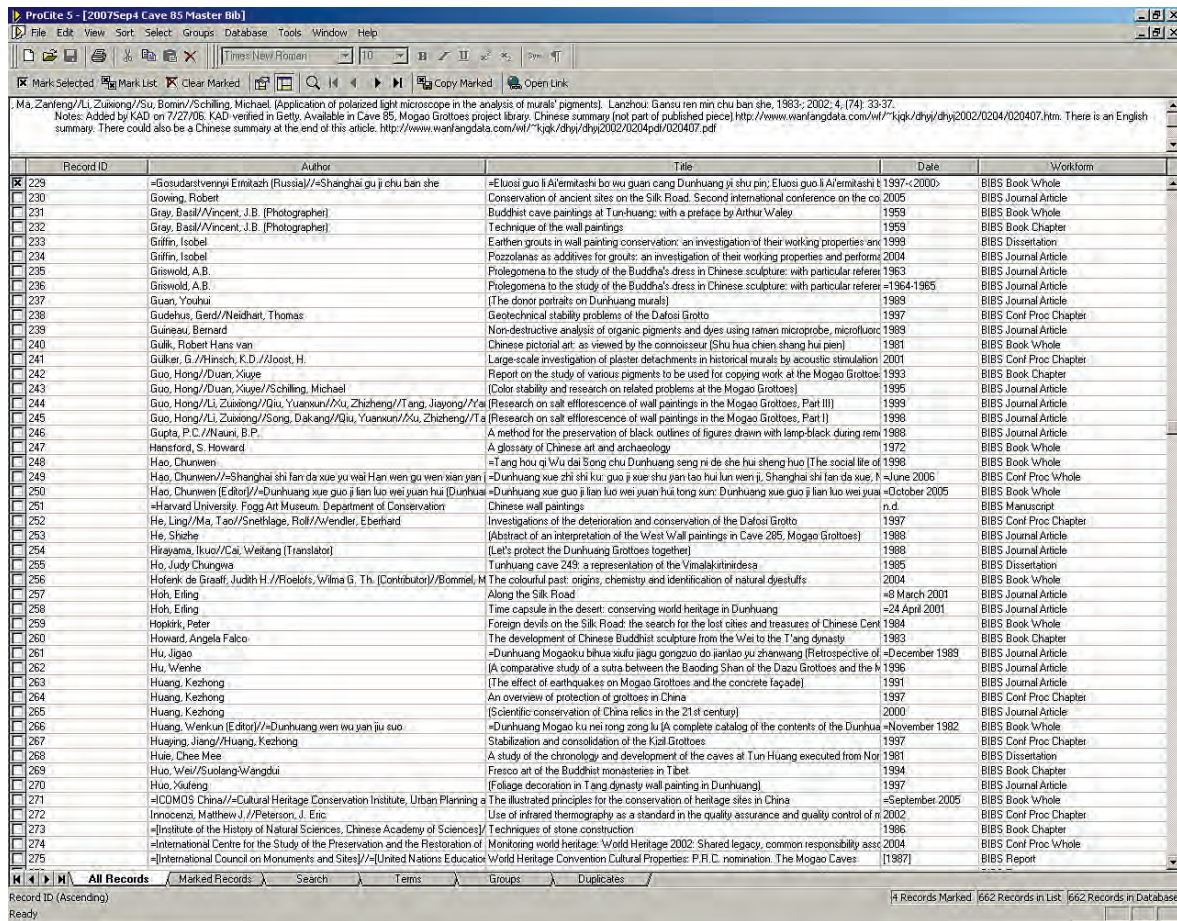


FIGURE 2 Project bibliography in ProCite® (a product of the Thomson Corporation).

Types of Data

As part of the information gathering, assessment, testing and development, implementation, and monitoring and maintenance phases of the project (see Piqué et al., this volume), many types of information were collected and created. The initial information-gathering phase included collection of written and oral sources on the historical context of the commissioning and construction of the cave in the late Tang dynasty and art historical and iconographic research of its wall paintings and sculptures. The history of interventions was also undertaken by consulting treatment reports and interviewing Dunhuang Academy conservators. This led to the creation of a bibliography specific to cave 85 and relevant to wall paintings on earthen supports generally. As the project progressed, the list of references grew; the project bibli-

ography now contains more than seven hundred records in hard copy and electronic form (fig. 2).

Visual resources were also collected to help reconstruct the physical history of cave 85, including the earliest known photograph of the cave, taken by the Russian expedition to the Mogao Grottoes in 1914 (fig. 3). Taken some fifty years before the construction of the cliff facade, the photograph shows the paintings in the antechamber exposed to the exterior and the condition of the site at that time. Photographs from explorers and travelers who visited the Mogao Grottoes in the early twentieth century have contributed significantly to understanding the history of the site, its deterioration, and whether or not deterioration was treated. This kind of information has been fundamental to understanding the processes and the causes of deterioration affecting the cave today. Photographs of the wall paintings in cave 85 taken by James Lo and Lucy Lo in 1943–44 provide an important record of the condition of the wall paintings before any modern intervention. Photographs by a young American woman, Irene Vongehr Vincent, who traveled to Dunhuang in 1948,



FIGURE 3 Earliest known photograph of cave 85, taken by the Russian expedition led by Sergei Oldenburg (1863–1934) to the Mogao Grottoes in 1914–15. Reproduced by permission of the State Hermitage Museum of Russia

also contribute to our records (Vincent 1953), in addition to the many photographs taken over the years by the Dunhuang Academy, which was established in 1944.

In addition, current photographs, including the more than five hundred (color and black-and-white) taken as part of the comprehensive documentation of the condition of the paintings at the start of the Getty Conservation Institute–Dunhuang Academy project, are also part of the database. These photographs were used as base maps for graphic condition recording of the cave. The condition was manually recorded on transparencies over the photographs and then transferred into digital format as CAD drawings (fig. 4). To supplement the condition assessment, an illustrated terminology was created to standardize communication between team members, to aid in the recording of condition, and to show the severity of conditions recorded. The glossary includes an agreed-on term and definition for each condition phenomenon (in both English and Chinese) and is illustrated with detailed photographs. The glossary helped to establish greater objectivity in a normally subjective recording process, facilitating both the recording and the subsequent interpretation of condition records. (For more information on the condition recording process in cave 85, see Xu Shuqing et al., this volume.)

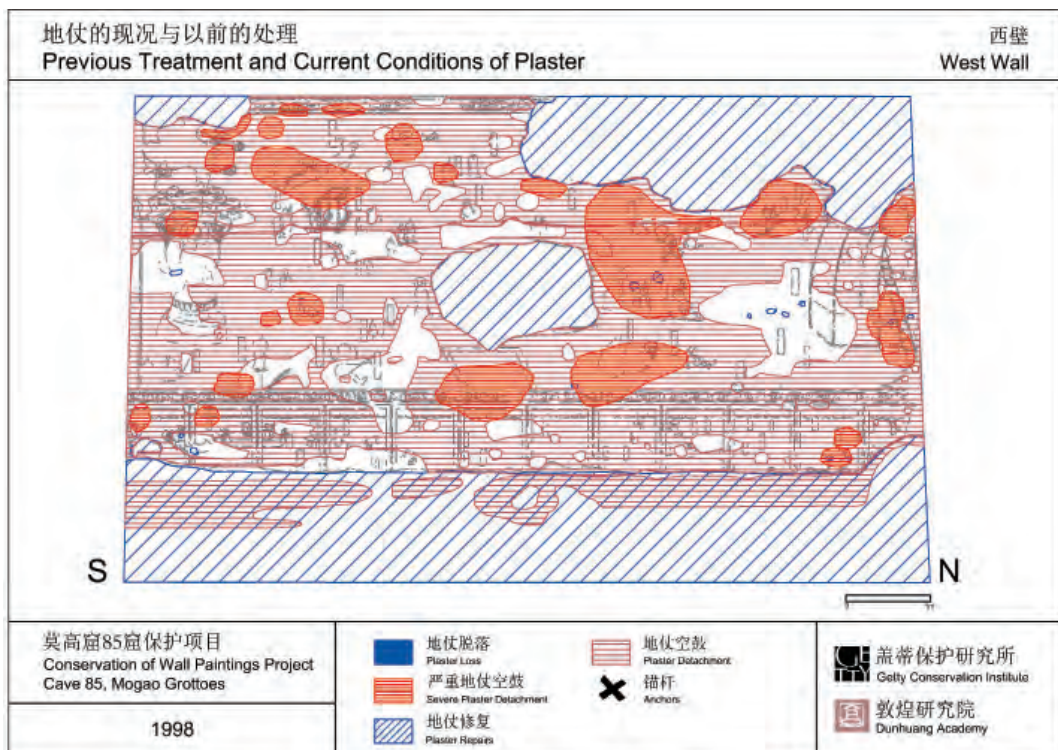


FIGURE 4 The condition of the wall paintings was recorded on transparencies laid over photographs and then transferred into digital format as CAD drawings. This image shows the west wall of the cave with areas of loss and plaster detachment graphically indicated.



FIGURE 5 An example of the reports created for each individual sample.

Sampling was undertaken to characterize the original materials of the painting and to understand painting techniques. Each sample was documented, and analytical tests were employed depending on the particular questions to be answered. A separate report was then created for each sample (fig. 5). This included a description of the sample, its location, sampling rationale, and results of the analysis. The raw data resulting from each analysis were also archived separately to allow for future reference and study.

Environmental monitoring generated immense quantities of data, including exterior and interior conditions such as temperature and relative humidity, as well as total rainfall accumulation and rainfall intensity (see Maekawa et al., this volume). These data were systematically stored over the course of the project in collaboration with members of the environmental team.

As part of the testing and development of treatments, laboratory and in situ testing were documented, including the research and testing of grout formulations for use in treating detached painted plaster. Some eighty different grout formulations were subjected to rigorous testing (see Rickerby et al., on development and testing, this volume). Following testing, treatments were implemented and documented using graphic documentation and photography. For future monitoring, areas treated were identified and recorded to create baseline documentation.

Integration, Manipulation, and Presentation of Information

Given the complexity of the deterioration mechanisms, information from individual investigations alone does not always provide a complete understanding. There is a need to integrate information with related investigations and to visually display the data in a clear manner. Understanding the deterioration of the paintings involved integration and visual presentation of information from different disciplines.

Preliminary investigations identified soluble salts as the primary cause of both surface and subsurface deterioration. A salt survey undertaken to confirm this hypothesis included the sampling of forty-seven microcores, each taken at four or five incremental depths into the upper 10 millimeters of the plaster, resulting in nearly two hundred samples (fig. 6). The incremental depths of the samples correspond



FIGURE 6 Plaster microcores being sampled as part of a comprehensive salt survey. Each core was taken at four or five incremental depths into the upper 10 millimeters of the wall where paint has been lost. The samples were analyzed to identify ions of soluble salts present and their topographic and stratigraphic distribution throughout the cave.

to the painting technique and stratigraphy. The microcores were then analyzed to identify ions of soluble salts present and their topographic and stratigraphic distribution.

The data were visually presented to correlate analytical with conservation data. The location of the microcores was superimposed over the CAD condition drawings. Each microcore has a corresponding data chart showing the main soluble ions divided by incremental depth. This type of plotting was done for all areas and clearly shows the enrichment

of soluble salts toward the rear (west) end of the cave (fig. 7a), by comparison with the east end (fig. 7b). It establishes a direct correlation between the high salt content of the plaster and the poor condition of the wall paintings and identifies the constraints and limitations of undertaking treatment in these problem areas. Presenting the data visually helps to interpret the vast amount of tabulated data generated as part of the microcore sampling (table 1).

Table 1 Results of the Salt Survey in Cave 85 Showing Soluble Ion Content of the Plaster Microcores

	A	B	C	D	G	H	I	J	K	L	M	N	O	P	Q	R
1																
2																
3						Milliequivalents per 100 grams of plaster										
4		Sample Location	D	Sample depth, mm	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Total anions	Total cations		Ratio of Total Anions to Total Cations	
5		West wall	15A	0-2mm	20.9	1.02	18.62	39.37	1.18	0.80	6.85	40	48		84	
6		West wall	15B	2-5	24.5	1.14	14.66	44.22	1.04	0.44	2.38	40	48		84	
7		West wall	15C	5-7	24.3	1.27	18.27	46.63	1.07	0.49	2.84	44	51		86	
8		West wall	15D	7-10	35.6	1.18	13.49	52.14	1.13	0.51	2.35	50	56		90	
9																
10		West wall	16A	0-2	9.9	1.16	30.43	24.02	0.85	0.94	19.10	41	45		92	
11		West wall	16B	2-5	38.2	1.82	17.67	57.18	1.10	0.79	5.49	58	65		89	
12		West wall	16C	5-7	70.8	1.71	10.84	81.88	1.05	0.60	2.89	83	86		96	
13		West wall	16D	7-10	34.3	1.86	11.17	50.61	0.97	0.44	2.71	47	55		87	
14																
15		West wall	17A	0-2	64.9	1.21	22.69	82.21	1.10	0.74	7.14	89	91		97	
16		West wall	17B	2-5	25.7	0.92	16.54	45.61	0.96	0.41	3.30	43	50		86	
17		West wall	17C	5-7	53.1	1.06	13.87	69.08	1.02	0.33	2.39	68	73		93	
18		West wall	17D	7-10	49.2	1.30	13.29	65.57	1.20	0.43	2.46	64	70		92	
19																
20		West wall	18A	0-2	44.4	1.07	13.32	51.96	0.95	1.44	8.13	59	62		94	
21		West wall	18B	2-5	24.4	1.46	11.97	37.40	0.90	0.88	5.40	38	45		85	
22		West wall	18C	5-7	51.9	2.51	7.71	62.42	0.94	0.72	2.75	62	67		93	
23		West wall	18D	7-10	57.7	2.39	6.38	69.05	0.88	0.59	2.00	66	73		92	
24																
25		West wall	19A	0-2	6.2	0.62	19.25	17.42	0.58	0.65	10.93	26	30		88	
26		West wall	19B	2-5	33.1	0.97	15.25	49.06	0.86	0.74	6.13	49	57		87	
27		West wall	19C	5-7	38.2	1.28	10.39	53.84	0.87	0.34	2.20	50	57		87	
28		West wall	19D	7-10	34.7	1.11	7.90	48.85	0.79	0.24	1.49	44	51		85	
29																
30		West wall	20A	0-2	10.8	0.93	17.36	20.78	0.67	0.86	10.65	29	33		88	
31		West wall	20B	2-5	55.1	1.52	8.82	64.54	0.86	0.70	3.50	65	70		94	
32		West wall	20C	5-7	39.1	1.48	5.07	50.10	0.81	0.42	1.58	46	53		86	
33		West wall	20D	7-10	34.3	1.82	7.80	46.05	0.86	0.57	2.29	44	50		88	
34																
35		West wall	21A	0-2	37.1	1.30	33.34	59.82	1.19	0.84	11.77	72	74		97	
36		West wall	21B	2-5	20.6	1.22	10.77	37.44	0.89	0.28	1.90	33	41		81	
37		West wall	21C	5-7	48.1	1.11	13.45	62.34	0.92	0.44	3.36	63	67		93	
38		West wall	21D	7-10	44.8	1.74	30.58	62.72	1.22	0.89	14.17	77	79		98	
39																
40		West wall	22A	0-2	6.4	0.67	22.62	19.30	0.69	0.67	12.23	30	33		90	
41		West wall	22B	2-5	49.2	1.43	20.38	67.36	0.96	0.83	7.03	71	76		93	
42		West wall	22C	5-7	62.6	1.41	15.05	78.37	0.99	0.70	4.86	79	83		95	
43		West wall	22D	7-10	31.3	1.47	10.19	46.03	0.94	0.34	2.34	43	50		87	
44																
45		West wall	23A	0-2	4.7	0.41	10.67	12.33	0.46	0.38	6.61	16	20		80	
46		West wall	23B	2-5	22.5	0.91	10.22	37.93	0.71	0.27	2.14	34	41		82	
47		West wall	23C	5-7	34.5	0.83	7.79	47.51	0.67	0.18	1.22	43	50		87	
48		West wall	23D	7-10	22.0	0.91	7.22	36.36	0.68	0.20	1.16	30	38		78	
49																
50		West wall	24A	0-2	4.2	0.45	33.61	10.22	0.87	0.97	27.47	38	40		97	
51		West wall	24B	2-5	60.0	1.08	23.43	68.62	1.44	1.49	14.34	85	86		98	
52		West wall	24C	5-7	43.3	1.57	16.66	54.64	1.84	1.26	8.00	62	66		94	
53		West wall	24D	7-10	32.5	1.54	15.70	45.10	1.77	1.18	7.97	50	56		89	

FIGURE 7a The data from each microcore was charted and super-imposed over the CAD condition drawings. This type of plotting helped to visualize the enrichment of salts toward the rear (west) end of the cave and established a direct correlation between salt content of the plaster and deterioration of the wall paintings. This image shows the west wall with high soluble ion content.

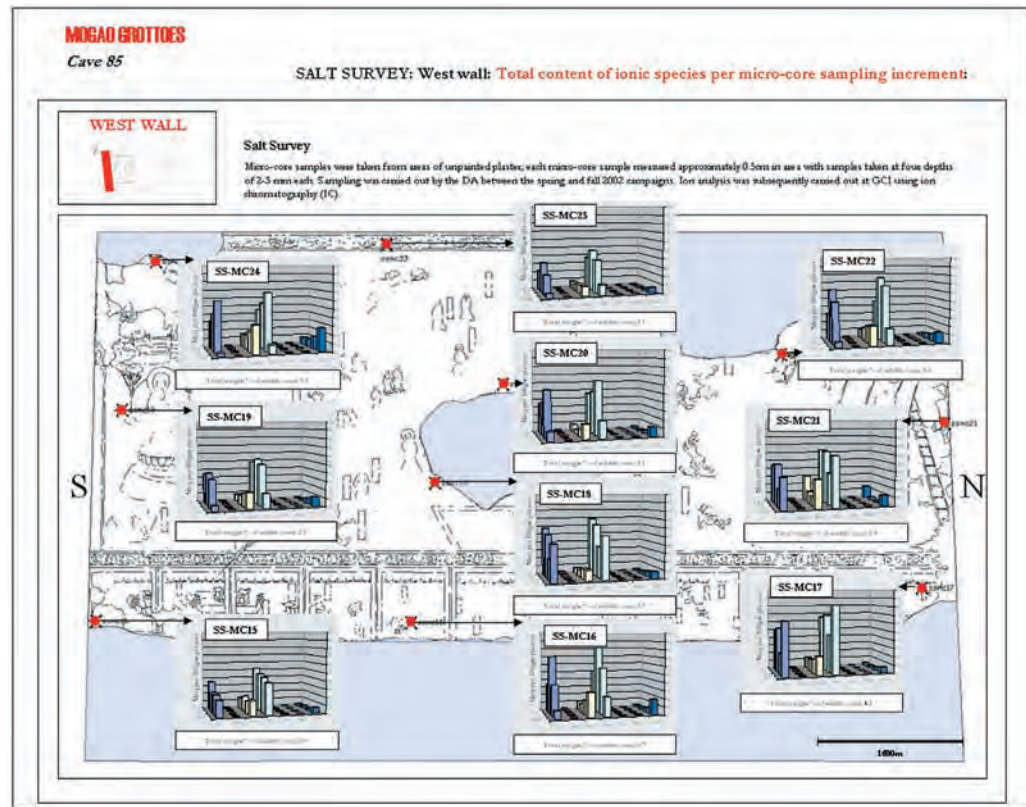
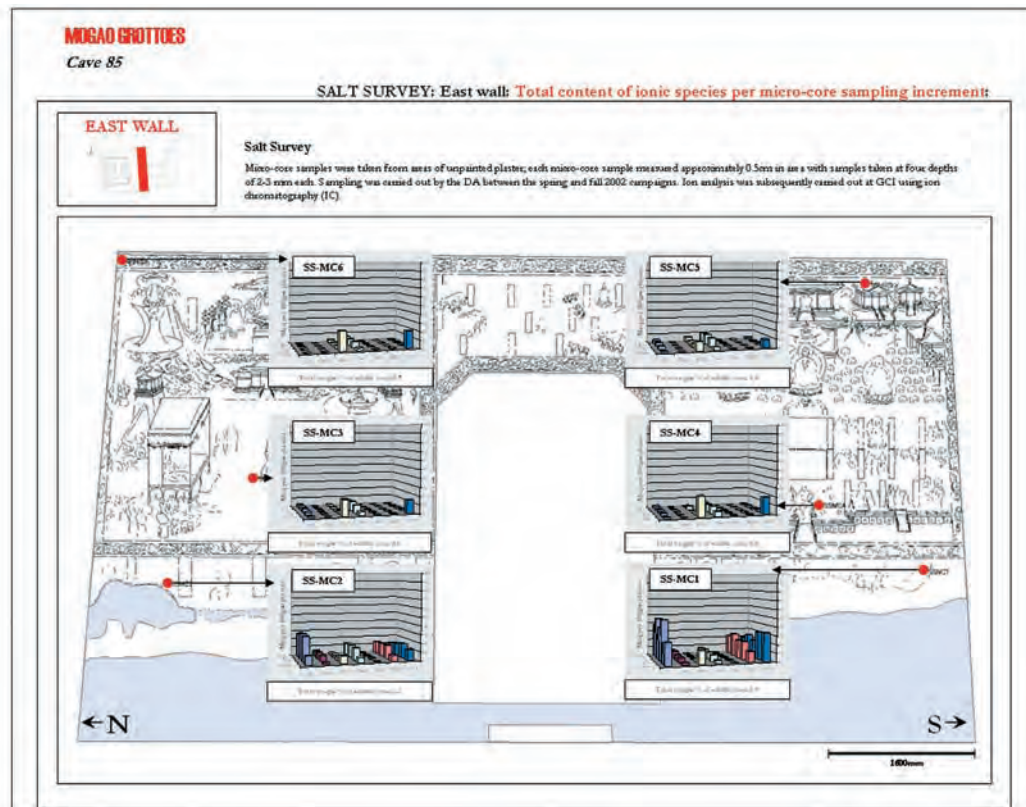


FIGURE 7b Results of the salt survey on the east wall. The soluble ion content of microcores sampled on this wall is significantly lower than that of microcores analyzed from the west wall, and the condition is significantly better than that of the west wall.



Conclusion

The cave 85 project is an example of the management challenges created by a large body of information during a complex, multiyear, interdisciplinary project involving a sizable team. The project overcame these challenges through the establishment of an information management system, the appointment of an information manager responsible for the integration of data from different investigations, and the commitment of the project team. The project database is shared between the two partner organizations. The experience gained from the management of this large body of data has had wider application for the conservation of other caves at the Mogao Grottoes and at similar projects of this scale in China.

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Hugo Houben is cofounder of CRATerre, the International Center for Earth Construction, a scientific organization within the School of Architecture of Grenoble, France. He is also responsible for the UNESCO Chair for Earthen Architecture (Constructive Cultures and Sustainable Development) and codirector of Project TERRA. He has been specializing in earth construction since 1972.

Huang Huaiwu is an associate researcher at the Guangxi Zhuang Ethnicity Autonomous Region Museum. His research interest is conservation of outdoor and intramural cultural properties. He directed the sampling, environmental data analysis, and experimentation subprojects for the project on mechanisms of deterioration and preventive measures for the Huashan rock paintings, sponsored by the State Administration of Cultural Heritage. He has published numerous articles on rock painting conservation.

Huang Jizhong is deputy director of the Yungang Grottoes Academy in Shanxi province. He received a master's degree from the heritage conservation department of Fudan University in 1996 and a Ph.D. in geology from the Chinese Academy of Geological Sciences in 2005. He has researched stone and grotto conservation at Yungang Grottoes since 1988. Currently, his main research areas are the impacts of environmental pollution and water on stone statues and nondestructive tests on stone relics. Huang has published extensively on these topics. He has received both a National Conservation Science and Technology Renovation Award and the Shanxi Province Scientific Technology Progress Award in 2005.

Huang Kezhong graduated from the Beijing Geological Institute in 1961. For more than forty years, he has been involved in the research and conservation of grottoes, ruins, and burial sites. Now retired from positions as senior engineer and deputy director at the China National Institute of Cultural Property, he serves as adviser to the Chinese

Heritage Information and Consultation Center. Before retirement he was a researcher at the Dunhuang Academy, a professor at the Chinese Geological University and Northwestern University, and deputy chair of the Council of the Chinese Heritage Association and the Chinese Cultural Heritage Conservation Techniques Association.

Jumamedel Imankulov, director of the scientific research and design institute Kyrghyzrestoration, has been studying Kyrghyzstan architecture for more than thirty years. Since 1997 he has also been head of the Department of Architectural Heritage Restoration at the State University of Construction, Transport, and Architecture. He has published extensively on the history and theory of architecture in central Asia and has participated in numerous state and international seminars, training events, symposia, and conferences as an expert on conservation and restoration.

Shuichi Iwata, geologist, has been studying the minerals and microfissures in complex rock formations in Japan, Egypt, and China.

Jiang Baolian received a bachelor's degree in archaeology in 1984 from Northwestern University, China. Her primary research interest is historical investigation and research in cultural heritage.

Jin Hongkui has been deputy director of the Palace Museum since 2002 and is also in charge of ancient building restoration and conservation. He graduated from Beijing University's history department in 1982 with a major in archaeology. Between 1982 and 2002 he worked first in the cultural heritage group of the Ancient Architectural Research Institute of the Beijing Municipal Cultural Heritage Bureau and subsequently at the State Administration of Cultural Heritage in the Department of Sites and Monuments Protection. His main tasks were dealing with survey of immovable heritage, conservation, restoration, and management. His important academic achievements and publications include participation in the development of the China Principles as a member of the core group, chief editor and writer for the Simatai Great Wall publication, and many articles.

Edith Joseph received a B.S. degree in chemistry from the Université de Nantes, France. She then specialized in organic and analytical chemistry and completed, at the same university, an advanced postgraduate studies diploma in

chemistry and materials in 2001. She is currently participating in a European research project that aims to develop and evaluate new treatments for the conservation-restoration of outdoor stone and bronze monuments and is completing a Ph.D. program at the University of Bologna, Italy.

Keigo Koizumi received his Ph.D in civil engineering in 2005 from Osaka University, Japan. His main research interest is the application of remote sensing to monitoring ground disasters and the global environment. He is an assistant professor at Osaka University.

Christian Lahanier is currently head of the documentation and imaging technologies department at the Centre de Recherche et de Restauration des Musées de France (C2RMF). From 1968 to 1984 he managed the Department of Physics at the Laboratoire de Recherche et de Restauration des Musées de France (LRMF) and developed X-ray technologies. In 1984 he became head of the laboratory at LRMF and acquired a particle accelerator. From 1989 to 2002 he managed or contributed to ten European Union–Research and Technology Development projects, setting up new 2D and 3D digital technologies, relational database management systems to give access, through a multilingual thesaurus, to the rich scientific documentation held at the C2RMF.

Lan Riyong is a senior researcher at Guangxi Zhuang Ethnicity Autonomous Region Museum. His research focuses on museum-held artifacts. He directed the evaluation of artistic value and the preservation environment subprojects for the causes of deterioration and preventive measures for the Huashan rock paintings project, sponsored by the State Administration of Cultural Heritage. He has published numerous articles on rock paintings, as well as several monographs.

Heinz Langhals studied chemistry in Münster, Germany, and received his Ph.D. in 1974. In 1984, after postdoctoral positions in Paris (organic chemistry) and in Zürich (physical chemistry), he became professor of organic chemistry at the Ludwig-Maximilians University, Munich. His research interests are in the field of macromolecular and organic chemistry.

Jean-Paul Laurent is a researcher at the National Center for Scientific Research (CNRS), working in the Laboratory of

Environmental Hydrology in Grenoble. He obtained a Ph.D. in 1986 in the thermal conductivity of earth. He is currently developing environmental monitoring systems.

Bo Lawergren, born in Sweden, holds a Ph.D. in nuclear physics from the Australian National University, Canberra. He is a professor emeritus at the Department of Physics and Astronomy, Hunter College of the City University of New York. Since the 1980s he has been active in two additional fields, musical acoustics and music archaeology (spanning Eurasia), resulting in fifty published articles.

Laurent Lévi-Strauss is deputy director and chief of the Tangible Heritage Section of the Division of Cultural Heritage, UNESCO. He is responsible for the coordination of UNESCO's operational activities in the field of cultural heritage conservation and preservation, notably in post-conflict and least-developed countries, including Afghanistan, Cambodia, Iraq, and North Korea, as well as throughout central Asia and in the Caucasus. This work involves some forty major operational activities, with a budget of more than US\$12.5 million.

Li Ping is associate researcher and head of the reception department at the Dunhuang Academy. She studied in the Asian and African department of the Beijing Second Foreign Language Institute and majored in Japanese between 1984 and 1986. From 1988 to 1990 she studied art history at National Hyogo University. Li Ping has translated from the Japanese *Travel with Gandhara Buddhism Arts* and *Iconography of Nirvana and Maitreya*, by Akira Miyali.

Li Weitang joined the Dunhuang Academy in 1977. His major assignments are copying of wall paintings, engineering survey and drawing, and cave measurement and survey. In the cave 85 project his tasks have been cave measurement and survey and recording of wall painting condition.

Li Yanfei has been a staff member at the Conservation Institute of Dunhuang Academy since 2001. Her main tasks are research on grotto sites, wall painting, and earthen sites conservation. She studied in the chemistry department at Xibei Normal University between 1997 and 2001.

Li Yunhe has been in the conservation field since 1956. He was appointed deputy head of the Dunhuang Academy's conservation department in 1980 and deputy director of the

Conservation Institute and director of the Yulin Grottoes in 1985. He retired in 1998 but remains a consultant to the Dunhuang Academy. He has received six awards from the Ministry of Culture, the State Administration of Cultural Heritage, and the Gansu Provincial Government and has published many professional papers.

Li Zuixiong is deputy director of the Dunhuang Academy, deputy head of the Chinese Cultural Relics Conservation Technology Council, and adviser for doctoral degrees at the Resources and Environment Institute, Lanzhou University. He received his Ph.D. in the conservation of cultural property from Tokyo National University of Fine Arts and Music and worked at the Gansu Provincial Museum from 1964 to 1995. His research focuses on the conservation of grottoes and earthen architecture sites, and he has participated in many conservation projects at such sites along the Silk Road.

Roland Lin Chih-Hung is a consultant at the Asia-Pacific Unit of the World Heritage Centre at UNESCO headquarters in Paris. He is in charge of UNESCO cultural heritage protection projects in central Asia as well as the World Heritage Silk Roads serial nomination central Asian section. In addition, Lin is a research fellow at the Centre de Recherche en Extrême-Orient de Paris-Sorbonne, IPRAUS at the Paris-Belleville Architecture School, and ATELAB at the Paris-La Villette Architecture School. He has published numerous specialized papers on the need to safeguard world and cultural heritage in Asia.

Liu Gang is a Dunhuang Academy staff member and has been involved in wall painting conservation projects with the Getty Conservation Institute and the Tokyo National Institute of Cultural Property. His main research area is environmental monitoring and digitizing techniques for applications to cultural heritage information. Currently, he serves on a standing committee of the Chinese Museum Association concerned with digitization and is deputy committee head of the information digitizing committee of the Chinese Cultural Heritage Association. He has participated in projects such as a computer storage and management system for Dunhuang wall paintings sponsored by the Gansu Provincial Scientific Committee, as well as others sponsored by the National Scientific Committee. In addition, he was involved in two phases of wall painting digitizing projects in collaboration with the Mellon Foundation. As a result of the collaboration, he was able to form a team at the Dunhuang Academy that

is capable of undertaking complicated, large-scale, two-dimensional digitizing for cultural heritage.

Liu Yang received a master's degree in computer science in 2005 from the Zhejiang University, China. His main research interest is the digitization of cultural heritage.

Lu Dongming is a professor of computer science at Zhejiang University, China. He directs a small team exploring the technology of cultural heritage digitization. His main research interest is the digitization, digital preservation, and virtual display of cultural heritage.

Lu Yanling earned a B.Sc. in chemistry from the Northwest Normal University, China. She worked at the conservation laboratory of the Gansu Provincial Museum and in 2002 became its deputy head and an associate professor. At present she is a conservation scientist at the Shenzhen Municipal Museum.

Jean-Louis Luxen, who trained in law and economics, has been Administrateur Général, Department of Cultural Affairs, Belgium, since 1981. He is also a professor at the Catholic University of Louvain and a member of the Commission Royale des Monuments et Sites, Brussels. From 1989 to 1993 Luxen served as president of the Cultural Heritage Committee of the Council of Europe; from 1993 to 2002, as secretary general of ICOMOS, with an active involvement in the implementation of the World Heritage Convention; and since 2001, as president of CHEDI (Culture, Heritage, and Development–International).

Ma Qinglin earned a Ph.D. in chemistry from Lanzhou University, China. He was a visiting conservation scientist at the Getty Conservation Institute in 2001 and a postdoctoral fellow at the Inorganic Chemistry Institute of Zurich University in 2003. He worked at the Gansu Provincial Museum from 1986 to 2004 as head of the conservation laboratory and later become the deputy director of the museum. At present he is a senior scientist and deputy director of the China National Institute of Cultural Property in Beijing.

Ma Tao, who holds a master's degree in environmental science from Beijing University, has been chief conservator at the Xi'an Center for the Conservation and Restoration of Cultural Property, Shaanxi province, since 1989. His current

work focuses on the conservation of stone, clay sculptures, and polychromy and environmental studies.

Ma Zanfeng, assistant researcher in the Conservation Institute of the Dunhuang Academy, has a master's degree in conservation from Xi'an Northwestern University. He is currently a science and technology doctoral candidate at the University of Beijing. Since 1997 he has worked at the Conservation Institute of the Dunhuang Academy.

Richard Mackay was chair of the Jenolan Caves Reserve Trust from 2001 to 2004 and a board member from 1992 to 2004. He is a director of Godden Mackay Logan, a leading Australian heritage consultancy firm. He has expertise in cultural resource management and extensive experience as a team leader, project director, and facilitator for heritage management and archaeological projects.

Shin Maekawa is a senior scientist in charge of the Environmental Studies Laboratory of the Getty Conservation Institute, overseeing and conducting research on climate control technologies for historic buildings as well as microclimates of cultural objects for conservation. He conducted nitrogen anoxia research for conservation that resulted in the publication of three books. Maekawa earned a B.S. in engineering applied mechanics from the University of California, San Diego, an M.S. in mechanical engineering from the University of California, Los Angeles, and a Ph.D. in conservation science from Tokyo National University of Fine Arts and Music. He is a registered professional engineer (mechanical) in the state of California.

Fred H. Martinson is an art historian specializing in the history of Buddhist art. He received a Ph.D. in Japanese and Chinese art history from the University of Chicago in 1968 under the mentorship of Harrie A. Vanderstappen. He has lived and traveled in Japan, Hong Kong, China, and Taiwan. Martinson retired from the University of Tennessee in May 1998 as professor emeritus of art and a member of the Asian Studies Committee.

Tadashi Masuya has extensive experience in geophysical exploration for disaster prevention and civil construction. Since 1995 he has been a member of and has guided many project teams working on stone heritage conservation, for example, conservation of the Great Sphinx.

Joy Mazurek has been an assistant scientist at the Getty Conservation Institute since 1998. She specializes in the identification of organic materials by gas chromatography–mass spectrometry. She obtained a master’s degree in biology, with emphasis in microbiology, from California State University, Northridge, and has a B.S. degree in biology from the University of California, Davis. She is currently using antibodies to identify binding media.

Rocco Mazzeo received a degree in chemistry in 1980 from the University of Bologna, where he is professor of chemistry for restoration and director of the bachelor’s and master’s degree courses in science and technology for the conservation of cultural heritage. His current research interests are the analysis of the materials and production techniques of mural paintings and their conservation, as well as Renaissance outdoor bronze monuments.

Pan Yunhe is a graduate of Tongji University and holds a master’s degree from Zhejiang University. He was president of Zhejiang University, having been a professor of computer science there. In 1997 he was elected a member of the Chinese Academy of Engineering and is a pioneer in the field of intelligent computer-assisted design and computer art. His intelligent computer-assisted design system for art pattern creation has resulted in remarkable profits in the textile industry. Pan is currently vice president of the Chinese Academy of Engineering and an alternate member of the 17th Communist Party of China Central Committee.

Anne Pantet obtained her Ph.D. from the Institut National des Sciences Appliquées in Lyon in 1991. She is currently assistant professor of civil engineering at the University of Poitiers, working on the structural-mechanical property relationship in clays with variable water content.

Chunze Piao, a geological engineer, received his engineering geology degree from the University of Jilin, China, in 1996, and his master’s degree from the Department of Global Architecture at the University of Osaka, Japan, in 2001. Since 2004 he has been employed by the Hytec Company, a geology consulting firm in Japan. His main research interests are geotechnical and hydrogeological investigations.

Francesca Piqué earned a diploma in wall painting conservation and an M.S. from the Courtauld Institute of Art, University of London. She worked at the Getty Conservation

Institute for more than twelve years on archaeological, mosaic, and wall painting conservation projects worldwide. She currently resides in Italy. Piqué has published numerous articles and two books on wall painting and mosaic conservation and teaches in various institutions.

Armin Portmann is a retired specialist in electron microscopy working at the University of Zurich. He provided SEM/EDX measurements for the study of ancient synthetic blue and purple pigments.

Silvia Prati received a degree in chemistry in 1999 and a Ph.D. in environmental chemistry in 2002 from the University of Bologna, Italy. Her main research interest is the application of analytical pyrolysis coupled with gas chromatography–mass spectrometry to address problems concerning the conservation of cultural heritage.

Qiao Hai is a wall painting conservation technician and has been employed by the Dunhuang Academy since 1999 in conservation projects at the Mogao and Yulin Grottoes, the Potala Palace, and other international collaborative projects such as the cave 85 and cave 53 projects and the Mogao Grottoes site carrying capacity study. He also participated in training courses, including the Wenzhou polychrome statue and earthen architecture conservation programs. He graduated from the Xi’an Army Academy Department of Economic Management.

Qiu Fei joined the Conservation Institute of Dunhuang Academy in July 2001. His main task is windblown sand monitoring and research at the Mogao Grottoes. He graduated from the Ecology Engineering program at Gansu Forestry Technology Institute in June 2001, after which he enrolled in the Beijing Forestry University Adult Educational Academy forestry program between 2001 and 2003 and received a diploma.

Leslie Rainer is a conservator of wall paintings and senior project specialist at the Getty Conservation Institute (GCI). She has worked on conservation projects internationally, specializing in decorated surfaces on earth. She was a member of the GCI team on the Mogao project from 1998 to 2001. She received an independent master’s degree in the conservation of architectural surfaces from Antioch University in 1991 and a certificate from ICCROM in mural paintings conservation in 1990. Rainer won the Rome Prize

Fellowship in Conservation and Historic Preservation in 1998–99. She is a member of the American Institute for the Conservation of Historic and Artistic Works, the International Institute for Conservation, and the International Commission on Monuments and Sites.

Akbar Rakhimov is director of the Rakhimov Museum and head of the UNESCO-sponsored school for traditional ceramics in Tashkent. He is a practicing potter, artist, and designer whose work is displayed in museums in Russia, Germany, Japan, Turkey, France, and Uzbekistan. Awarded a Distinguished Master of Ceramics of Uzbekistan in 1991, he became a full member of the Uzbek Academy of Arts in 1997 and has also received the UNESCO certificate of achievement. He was a co-organizer of the symposium and exhibition *Blue Ceramic of Samarkand*, sponsored by UNESCO in 1998, and the Symposium on Uzbek Traditional Ceramics in September 2001. He traces a continuous family lineage of ceramic masters to the late eighteenth century.

Alisher Rakhimov, the son of Akbar Rakhimov, is a distinguished ceramic master. He is a teacher and administrator at the school for traditional ceramics and also maintains his own ceramics studio. He has mastered some of the techniques of the black, brown, yellow, and blue Kashgari pottery as well as the *ishkor* process. He was awarded a fellowship to study in Japan at traditional workshops where overglaze enameling is practiced. In addition, he has presented workshops on Silk Road ceramic techniques and successfully exhibited his work.

Stephen Rickerby is a private wall painting conservator and has been a consultant on a number of Getty Conservation Institute projects, including the tomb of Nefertari in Egypt, the Royal Palaces of Abomey in Benin, and the cave 85 project at Mogao. He has been involved with conservation teaching in China, including the ongoing, three-year postgraduate course in wall painting conservation being held at Mogao. He also co-supervises the fieldwork sites of the Courtauld Institute of Art, London.

David Saunders joined the British Museum after twenty years in the scientific department at the National Gallery in London, where his areas of research included the effect of the environment on paintings and on artists' materials, preventive conservation, and the application of imaging techniques to the examination of paintings. He has been

an editor of the journal *Studies in Conservation* since 1990 and served on the technical committees for the 1994 and 2000 congresses. Since January 2003 he has been director of publications for the International Institute for Conservation (IIC) and a member of the IIC Council.

Michael R. Schilling is a senior scientist and head of the Analytical Technologies section at the Getty Conservation Institute (GCI). His research interests include analysis of natural organic materials used as paint media and varnishes, modern paints, and plastic sculptures. He has been involved in several GCI projects at the Mogao Grottoes since 1989.

Sekhar Chandra Set is an architect, city planner, and artist. He received a bachelor of architecture degree in 1966 from Calcutta University, a master's degree in city planning in 1971 from the Indian Institute of Technology, Kharagpur, and a Ph.D. in painting in 1991 from Rabindra Bharati University, Calcutta. He has been a lecturer at the Indian Institute of Technology, a guest lecturer at Rabindra Bharati University, and an assistant professor (reader) and department head at Bengal Engineering College. Set is the recipient of national awards in landscape architecture, painting, and music (violin). He is also a member of the Indian Institute of Architects and the Institute of Town Planning, India. His special fields of interest are urban aesthetics and wall paintings.

Lisa Shekede, a private wall paintings conservator, was a consultant on the cave 85 project at the Mogao Grottoes from 2000 to 2004. She currently co-supervises the fieldwork programs of the Courtauld Institute of Art master's degree program in wall painting conservation and is an instructor for the postgraduate course in wall painting conservation being held at Mogao. Her particular areas of expertise are the technology and conservation of wall paintings on earthen supports.

Shuya Wei is a scientist at the Institute of Science and Technology in Art, Academy of Fine Arts, Vienna, Austria. In 2007 she received her doctorate at the University of Technology in Vienna. Between 1999 and 2002 Shuya received two master's degrees, in the principles of conservation and conservation in archaeology and museums, from University College, London. As a graduate intern at the Getty Conservation Institute in 2003, she was involved in the investigation of materials used in decorative painting of Chinese Qing dynasty architecture, as well as the study

of wall painting degradation mechanisms at the Mogao Grottoes due to salt migration. Her current work focuses on the study of organic materials by a combination of pyrolysis–gas chromatography–mass spectrometry and Fourier transform infrared techniques.

Su Bomin is director of the Conservation Institute at the Dunhuang Academy and standing deputy director of the Ancient Wall Painting Conservation Science and Technology Research Center, State Administration of Cultural Heritage (SACH). He has received awards from SACH. He is the author of numerous professional articles. He was a visiting scholar in 2000–2002 at the Tokyo Art Institute and in 2006 at the Getty Conservation Institute.

Sharon Sullivan is the retired executive director of the Australian Heritage Commission and the former Australian government representative on the World Heritage Committee. She has worked and published extensively on cultural heritage management issues for thirty years, in Australia and overseas, including the United States, China, Africa, and Cambodia. She is the author of a range of publications, including, with Michael Pearson, *Looking after Heritage Places*, 2nd ed. (Melbourne University Press, 1998). Sullivan has been a cultural heritage consultant for the Australian government, the World Bank, the World Monuments Fund, the Getty Conservation Institute, and the government of the People's Republic of China. She is an adjunct professor at the University of Queensland, James Cook University of North Queensland, and the University of New England. She is a fellow of the Academy of the Humanities, an honorary life member of ICOMOS, a member of the Institute of Aboriginal and Torres Strait Islander Studies, deputy chair of the NSW Heritage Council and the Port Arthur Historic Site Authority, and chair of the National Cultural Heritage Forum. She has been awarded an honorary doctorate by James Cook University, and in January 2005 she was appointed an Officer in the Order of Australia for her service to cultural heritage conservation.

Sun Hongcai joined the Dunhuang Academy in 1972. Currently he is working in the academy's Digital Center. Between 1972 and 1996 he worked on wall painting and statue restoration in the Conservation Institute. He started documentation photography in 1977 and took the photographs used for documentation and for the wall painting condition assessment in the cave 85 project.

Sun Yihua is an associate researcher with the Conservation Institute, Dunhuang Academy. She has participated in many survey, planning, and restoration projects, among them the Binlin Temple, the Yulin Grottoes, and the Mogao Grottoes. Her major publication is a compilation of the architectural painting and grotto architecture at Mogao.

Tang Wei is a wall painting conservation technician and has been employed at the Dunhuang Academy since 2001. He has been involved in conservation projects at the Mogao Grottoes, the Yulin Grottoes, and the Lhasa Potala and Norbulinka Palaces, as well as international collaborative projects such as the cave 85 and cave 53 projects and the cave carrying capacity study at Mogao. He graduated from the Northwestern University (Xi'an, Shaanyi) Department of Cultural Heritage and Museum.

Chikaosa Tanimoto has been a professor of civil engineering at Osaka University, Japan, since 1997. He has chaired the international commission for the preservation of natural stone monuments since 1995. He guides a team exploring origins and movement of groundwater around the Mogao Grottoes.

Tie Fude has a doctorate from the Beijing Science and Technology University and is a professor at the China National Museum. His research interests include materials analysis, history of science and technology, and conservation technology. He has been involved in various projects, including nonmetallic replication of bronzes, control of corrosion of ancient bronzes, and preservation of wall paintings from Tang tombs.

Henri Van Damme has been a professor of physical chemistry and materials science at the Ecole Supérieure de Physique et Chimie Industrielles (ESPCI) in Paris since 1999. He is primarily interested in the chemico-mechanics of fine-grained cohesive materials and their interactions with polymers and has a growing interest in earthen materials and conservation. He is currently collaborating with CRATERRE-EAG, ICCROM, and the Getty Conservation Institute on Project TERRA.

Ron van Oers received a Ph.D. from Delft University of Technology (the Netherlands) in 2000 on research into the principles of Dutch colonial town planning between 1600 and 1800. Currently he is chief of unit for Latin America

and the Caribbean at UNESCO's World Heritage Centre. He is also a research fellow at Delft University. He is a voting member for the Netherlands in the ICOMOS International Scientific Committee on Cultural Routes.

Lucien M. van Valen received a master's degree in fine arts at the Gerrit Rietveld Academy in Amsterdam (1981) and in Chinese languages and cultures at Leiden University (1997). In 2005 she received a Ph.D. from Leiden University, combining both her fields of interest in her thesis, "The Matter of Chinese Painting, Case Studies of Eighth-Century Murals." Her current research is on Chinese painting techniques from 1200 to 1644.

Amy Vandiver is a senior remote sensing and software engineer at Scientific Solutions, Inc., and has worked on a variety of appropriate technology, archaeology, and underwater acoustics problems. She has dual B.A. degrees in geoscience and electrical and computer science and an M.S. in underwater acoustic sensing of archaeological sites from the Massachusetts Institute of Technology. Her main interests are geological resource survey, telemetry of whales, critical parameters sensing and evaluation of racing sailboats, and wilderness emergency medicine.

Pamela B. Vandiver is a professor at the University of Arizona, where she directs the Ph.D. program in heritage conservation science. Previously, she was a senior research scientist at the Museum Conservation Institute of the Smithsonian Institution. She received M.S. and Ph.D. degrees in materials science and engineering from the Massachusetts Institute of Technology, but she also has an M.A. in studio art and anthropology and a background of undergraduate studies in Western humanities and Asian studies. Her main research interests are in the analysis, reconstruction, and preservation of the ancient technologies of ceramics, glasses, plasters, pigments, and slags. In 2006 she received the Pomerance medal from the Archaeological Institute of America for scientific contributions to archaeology.

Harlan Wallach is the U.S.A. project director and media architect for academic and research technology at Northwestern University in Evanston, Illinois, where he leads research initiatives in the digital humanities and cultural heritage. He has worked with the Dunhuang Academy for more than ten years, advising on digitization projects. He has led similar efforts elsewhere in Asia as well as in Africa.

Wang Hui has been engaged in the conservation of historic buildings since he graduated in 1990 from Tongji University, Shanghai. He was employed at the Hebei Provincial Conservation Institute of Historic Buildings and the Hebei Provincial Administration of Cultural Heritage. From 1997 to 1999 he worked in Tibet as chief engineer for the conservation programs in the Ali region. Sponsored by the Ford Foundation, he completed his M.Phil. degree at the University of Bath, U.K., in 2006.

Wang Jinyu is an associate researcher in the Conservation Institute at the Dunhuang Academy. He is also a committee member of the Chinese Society for History of Science and Technology and of the Chinese Cultural Heritage Association. He graduated from the Department of Chemistry at Lanzhou University in 1978 and obtained a master's degree in heritage conservation from Fudan University in 1990. He has been involved in some thirty conservation research projects at the Mogao Grottoes, including international projects with the Getty Conservation Institute and the Tokyo National Research Institute of Cultural Properties. He has published some two hundred articles. His major publication is a volume on the science and technology of painting at the Mogao Grottoes.

Wang Tao is director of the Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Science. He is director of the International Center for Research and Training on Desertification Control, organized by the United Nations Environmental Program and the Chinese National Environmental Protection Agency. In addition, he is chair of the International Desert Research Association and chief editor of the *Journal of Chinese Deserts*. He has been in charge of or involved in many national projects and received the Chinese Science Academy Science and Technology Improvement Award, second rank, in 1997.

Wang Wanfu is deputy director of the Conservation Institute at the Dunhuang Academy, as well as deputy director of ancient wall painting conservation at the National Scientific Research Center and deputy chair of the China ICOMOS grotto sites conservation committee. His research fields are wall painting conservation, environmental research in arid climates, and management of grotto sites.

Wang Xiaowei graduated from the computer science department at the Normal University in 1998. Since graduation

he has been at the Dunhuang Academy. Currently, he is in charge of wall painting conservation and information and documentation management. In the cave 85 project he was tasked with digitizing wall painting condition documentation. He is enrolled in the wall painting conservation master's degree course of Lanzhou University and the Dunhuang Academy with the support of the Courtauld Institute of Art and the Getty Conservation Institute.

Wang Xudong, deputy director of the Dunhuang Academy, majored in hydrogeology and engineering geology at Lanzhou University. In 2002 he earned a Ph.D. in cultural heritage protection from Lanzhou University. His research focuses on the conservation of grottoes and earthen architecture sites, and he has participated in many conservation projects at such sites along the Silk Road. He has published more than thirty papers, won nine national-level and provincial-level awards for his conservation projects, and been awarded two patents.

Susan Whitfield is director of the International Dunhuang Project at the British Library, where she has worked since completing her Ph.D. in Chinese history at the University of London. Her current research interests include the history of the eastern Silk Road, forgeries, Chinese historiography, and the role of central Asia in world history.

Hans-Georg Wiedemann, a retired industrial scientist, developed and established thermal analysis as an analytical method. He has conducted numerous archaeometric studies, especially of synthetic blue pigments, using primarily thermoanalytical methodologies.

Ferdinand Wild is a senior chemist with the research group of Heinz Berke at the University of Zurich. He is investigating modern routes to the synthesis of blue and purple pigments.

Lorinda Wong is a wall painting conservator and project specialist at the Getty Conservation Institute. She has worked on the Valley of the Queens project in Egypt and the conservation of Qing dynasty painted architectural decoration at Shuxiang Temple, Chengde. At the Mogao Grottoes she has been involved in both the conservation of wall paintings project in cave 85 and, most recently, the visitor carrying capacity study for the site.

Jan Wouters earned a Ph.D. in chemistry and biochemistry at the University of Ghent, Belgium, in 1978. Since 1982 he

has been a conservation scientist with a particular interest in the analysis of natural organic materials used in works of art and culture. He has been a contractant in several European research projects, an expert invited by the European Commission, a supervisor of Ph.D. theses, an organizer or co-organizer of international conferences on cultural heritage, a teacher of several aspects of conservation science, and the author of more than one hundred publications in journals, books, and congress proceedings. He is coeditor of *e-Preservation Science* and a member of the editorial board of *Restaurator*. He is a member of the Advisory Committee of the Netherlands Institute for Cultural Heritage (ICN), Amsterdam, the Netherlands. From 2005 to 2008 he was chair of the International Committee for Conservation of the International Council of Museums (ICOM-CC).

Xia Yin, a chemist, received a master's degree from Northwest University in Xi'an. Since 1998 he has been working in the conservation department of the Museum of the Terracotta Warriors and Horses of Qin Shihuang, Lintong. He specializes in materials analysis of archaeological objects.

Xie Riwan is a senior researcher at Guangxi Zhuang Ethnicity Autonomous Region Cultural Properties and Archaeology Institute. His research is focused on conservation and archaeology. He directed the assessment of historical value and experimental components of the project on the mechanisms of deterioration and preventive measures for the Huashan rock paintings project, sponsored by the State Administration of Cultural Heritage. He has published more than twenty articles on rock paintings.

Xu Shuqing joined the Dunhuang Academy in 1977. Her main tasks have been copying of wall paintings, archive management, and conservation work. She participated in projects at Qinghai Qitang Temple between 1990 and 1995 and a number of other national and international projects. She received a Conservation Science Innovation Award, second rank, in 2004 from the State Administration of Cultural Heritage as one of the participants in the cave 85 project. Xu received advanced training at Tokyo National Institute of Cultural Properties in 2001.

Xue Ping became a tour guide for the Dunhuang Academy's reception department in 1986. He studied at Shanghai Fudan University between 1993 and 1996 and specialized in cultural objects conservation techniques. He transferred to the

Dunhuang Academy Conservation Institute in 1989 to conduct cave environmental monitoring and research. In 2000 he was assigned as head of the environmental group, and in April 2002 he became a staff member. He has been enrolled in the Gansu Television and Broadcasting University and has worked on computer science technology and applications since 2006.

Yang Jinjian is a wall painting conservation technician and has been employed by the Dunhuang Academy since 1994. Between 1994 and 2000 he worked for the security department and then transferred to the Conservation Institute to conduct wall painting conservation work. He has been involved in conservation projects at the Mogao Grottoes, the Yulin Grottoes, the Potala Palace, and the Lanzhou Zhuangyan Temple. At the Mogao Grottoes he participated in the cave 85 and cave 53 projects and the site carrying capacity study. He also participated in various training courses, including those in the earthen architecture program and the wall painting and polychrome statue conservation and restoration program in 2003.

Yang Mangmang received a degree in chemistry in 1987 from Northwestern University, Xi'an. Her primary research interest is conservation of metal objects, textiles, and wall paintings. She was responsible for the conservation of gold and silver wares of the Famen temple and has also taken part in many important conservation projects in Shaanxi province.

Yu Zongren has been a staff member of the Conservation Institute of the Dunhuang Academy since 2000. His work mainly involves research on grotto sites, wall painting, and earthen site conservation. He studied at the chemistry department at Xibe Normal University between 1996 and 2000.

Yuan Sixun is a professor in the College of Archaeology and Museology, Peking University.

Mokhtar Zabat obtained a Ph.D. from the University of Orléans, France, for work on the structure and mechanical properties of thin clay deposits, with Henri Van Damme as supervisor. After a postdoctoral contract in nanosciences in Japan and another in Canada, he joined the University of Boumerdes, Algeria, where he is now an assistant professor of physics.

Zhang Guobin graduated from the Gansu Agriculture University in 2002 with a major in desert control. He has been employed by the Dunhuang Academy to conduct environmental monitoring and data analysis, including the cave 85 project, windblown sand control and mitigation system planning and research, and three Tibetan restoration projects since August 2002. His main research areas are grotto site conservation and environmental control. He has participated in the development of new types of growth promoter and its application to a vegetation wind fence.

Zhang Lizhu taught in a countryside middle school and researched Marxist theory in the publicity department of the Hebei Provincial Committee of the Communist Party before being transferred to the Hebei Provincial Culture Department to manage culture-related issues. In 1993 he was appointed director of the Hebei Provincial Museum. In 1997 he was appointed director of the Hebei Provincial Cultural Heritage Bureau. In 2005 he became an inspector at the Hebei Provincial Culture Department.

Zhang Lu is a senior engineer at the Dunhuang Academy. He joined the Dunhuang Academy Conservation Institute in 1999. His research focuses on the conservation of cave temples and earthen sites.

Zhang Weimin is a researcher at the Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Science. His main research area is windblown sand landforms and sand control engineering. He has been involved in projects applying surface 3D photography to study the dynamic process of crescent sand dune development and the process of desertification and its control in northern China. He received a number of awards as a project participant and has published many articles.

Zhang Wenbin was director-general of China's State Administration of Cultural Heritage within the Ministry of Culture between 1996 and 2004. After retirement, he continued as a member of the National Committee, Chinese People's Political Consultative Conference. His entire career has been in the field of archaeology and culture. In addition, he has held several senior positions within the provincial and national Chinese Communist Party system.

Zhang Yongjian, conservator, trained in Germany and Italy in the field of restoration of glass, ceramic, and metal objects.

Zhang Zhijun has been the deputy head of the conservation division of the Museum of Terracotta Warriors and Horses of Qin Shihuang since 1989 and is in charge of conservation of and research on the site and its artifacts. He graduated from Northwestern University, China, in 1982 with a major in chemistry and has worked at the museum since that time. He has been involved in many projects, among them conservation of the polychrome terracotta figures and restoration of the bronze chariot from the Qin tomb. These were granted second-rank National Science and Technology Awards. He has published more than forty articles and books. He also received the Shaanxi Outstanding Expert Award in 2003 and the National Outstanding Expert Award in 2004.

Zhen Gang received a degree in restoration and conservation in 1995 from Northwestern University, China. His main research interest is the conservation and restoration of cultural heritage.

Zheng Jun has been working in the field of conservation since 1986, focusing mainly on decorated surfaces of architecture and polychrome sculpture. He has conducted various projects and taught many training courses. He

received a B.Sc. in applied chemistry from Beijing University in 1986, a postgraduate diploma from the conservation of wall painting department at the Courtauld Institute of Art, University of London, in 1994. Between 2003 and 2007 Zheng undertook research at the Courtauld Institute on conservation planning for heritage sites. He was awarded a Ph.D. in 2008.

Zhong Shihang graduated from the Beijing Geology College and is currently a senior researcher at the China Academy of Railway Sciences. He has participated in and directed several sensing projects, including those at the Palace Museum; the Kizil, Yungang, and Longmen Grottoes; and Dazu Baodingshan. He has invented a number of techniques and published more than one hundred scholarly articles.

Zhou Shuanglin earned a Ph.D. in conservation from Peking University and is currently an associate professor in the university's College of Archaeology and Museology. He has directed several conservation projects, including one funded by the State Administration of Cultural Heritage, and has also published numerous articles.

Zhou Weiqiang received a bachelor's degree in chemistry in 1995 from Zhongnan University, China. His primary research interest is the conservation and restoration of cultural heritage.

The Getty Conservation Institute

The Mogao grottoes, a World Heritage Site near the town of Dunhuang in western China, are located on the edge of the Gobi Desert, along the ancient caravan routes—collectively known as the Silk Road—that once linked China with the West. Founded by Buddhist monks as an isolated monastery in the late fourth century, Mogao grew gradually over the following millennium, as monks, local rulers, and travelers carved hundreds of cave temples into a mile-long rock cliff, and adorned them with vibrant murals portraying episodes from Buddhist scripture, luxuriant portraits of Silk Road rulers, and richly detailed scenes of everyday life. The Mogao caves developed into a spiritual and artistic mecca whose renown extended from the Chinese capitals to the far western reaches of Central Asia.

Today there remain more than 490 grottoes, the walls of which are decorated with some 45,000 square meters of wall paintings, making Mogao one of the world's most significant sites of Buddhist art. This volume contains the proceedings of the second conference on the conservation of Silk Road grotto sites cosponsored by the Getty Conservation Institute and the Dunhuang Academy, under the aegis of the State Administration of Cultural Heritage of the People's Republic of China.

Neville Agnew, senior principal project specialist at the GCI, is the author of numerous publications in research chemistry and conservation, including (with two coauthors) the book *Cave Temples of Mogao: Art and History on the Silk Road*.



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