

METROPOLITAN MUSEUM STUDIES IN ART, SCIENCE, AND TECHNOLOGY



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Frontispiece: Detail of Suzanne de Court, Mirror: *Venus Mourning the Dead Adonis* (1975.1.1236; Figure 3a, page 159)

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Director's Foreword

Technical research entails looking closely at the surfaces of works of art and, beyond that, into their very fabric. This is amply demonstrated in Volume 2 of *Metropolitan Museum Studies in Art, Science, and Technology*. In these pages, we learn about the latest research on the sandstones used by the Khmer masons of the pre-Angkor and Angkor periods; the authorship of a Spanish medieval altarpiece in The Cloisters; the origins of sculptures associated with Buddhist caves of the Northern Qi dynasty; and the authenticity of copper figures from the mountains of southern Lebanon dating to about 2000 B.C. The authors of these studies used technical means to characterize structure and agency with the goal of advancing art-historical knowledge. Following a theme established in Volume 1 with a history of early conservation practices in the Metropolitan Museum, the examination and treatment of medieval polychrome wood sculpture in American collections are considered with parallel developments in collecting and display.

A series of technical notes, many of which highlight the research of conservation and conservation science fellows who work with Museum staff in the material study of the collections, expands the range of media, manufacturing processes, and modes of analysis presented here. The works of art under investigation include Egyptian hard stone sculpture, silvered Limoges enamels, French furniture decorated with Japanese lacquer, a landscape by the American painter Thomas Moran, the Museum's Lion Helmet, and gum dichromate prints by French Pictorialist photographers.

This volume underscores the Museum's mission to investigate the material nature of works of art in addition to their aesthetic qualities and cultural contexts. We thank The Andrew W. Mellon Foundation and Annette de la Renta for their continued support of conservation and conservation science fellows at the Metropolitan. I join the Editorial Board in gratefully acknowledging Ludmila Schwarzenberg Bidwell and her late husband Carl B. Hess, and members of the Visiting Committees of the Sherman Fairchild Center for Objects Conservation, the Sherman Fairchild Center for Paintings Conservation, the Sherman Fairchild Center for Works on Paper and Photograph Conservation, and the Department of Scientific Research for their generous support.

THOMAS P. CAMPBELL

Director

The Metropolitan Museum of Art

Acknowledgments

The Editorial Board most thankfully acknowledges the late Carl B. Hess, who provided substantial financial support for Volume 2 as well as for the inaugural volume of *Metropolitan Museum Studies in Art, Science, and Technology*. Over the years, we benefited not only from Carl's generous funding but also from his enthusiasm and encouragement, fueled by a deep commitment to scholarship in the fields of art, science, and technology.

We are grateful to Ludmila Schwarzenberg Bidwell, who has continued her late husband Carl's legacy in her generous support of Volume 2. Further support was provided by the members of the Visiting Committees of the Sherman Fairchild Center for Objects Conservation, the Sherman Fairchild Center for Paintings Conservation, the Sherman Fairchild Center for Works on Paper and Photograph Conservation, and the Department of Scientific Research, all of whom we thank enthusiastically for their contributions to this new publication dedicated to the conservation and technical investigation of works of art.

The Editorial Board would like to express its special appreciation to Thomas P. Campbell, Director, for his ongoing support, and to Lawrence Becker, Sherman Fairchild Conservator in Charge, Sherman Fairchild Center for Objects Conservation, for allotting precious departmental resources to this important initiative.

A large debt of gratitude is also owed to our dedicated and meticulous volume editor, Ann Hofstra Grogg, whose sense of style and order significantly enhanced the quality of this

publication, and to our indefatigable proofreader Sylvia Tidwell. We are also grateful to Nancy Sylbert, who applied her skill and creativity to the design of Volume 2. New object photography was undertaken by Teresa Christiansen, Paul Lachenauer, Oi-Cheong Lee, Eugenia B. Tinsley, Juan Trujillo, and Karin L. Willis. We thank them and Barbara Bridgers, General Manager for Imaging, The Photograph Studio, The Metropolitan Museum of Art, for their many contributions.

Finally, we thank our large group of anonymous peer reviewers, whose expertise and insights have helped ensure the consistently high quality of the manuscripts. The same is true for our colleagues in the Museum, especially Peter Barnet, Senior Curator, Department of Medieval Art and The Cloisters; Federico Carò, Associate Research Scientist, and Tony Frantz, former Research Scientist, Department of Scientific Research; Elizabeth Mankin Kornhauser, Alice Brown Pratt Curator of American Paintings and Sculpture, The American Wing; and Andrew Winslow, Senior Departmental Technician, The Cloisters. Samir Iskander, Hung-hsi Chao, and Pamela Hernandez and Marina Ruiz-Molina kindly reviewed abstracts that appear here in Arabic, Chinese, and Spanish, respectively, assuring that these newly published studies are more accessible to foreign scholars in countries or regions that have special affinity with the works of art discussed herein.

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Petrography of Stone Used for Sculpture from the Buddhist Cave Temples of Xiangtangshan Dating to the Northern Qi Dynasty



Janet G. Douglas and John T. Haynes

ABSTRACT

Xiangtangshan in North-Central China is a major Buddhist cave temple complex dating to the Northern Qi dynasty (550–577). Its northern and southern caves once held stone sculptures that were removed from the site, starting in the early twentieth century, and are now in institutional and private collections throughout the world. The 2011 exhibition “Echoes of the Past: The Buddhist Cave Temples of Xiangtangshan” provided an excellent opportunity to study the Freer Gallery of Art’s collection of stone sculpture from Xiangtangshan together with related works in other museums. The current study began with petrographic characterization of limestone samples obtained from outside the Northern and Southern Xiangtangshan caves. Systematic description and analysis of the framework grains, cement, matrix, and porosity were then used as a basis for the study of limestone and marble sculptures traditionally associated with these sites. This approach allowed for the proposed sites of origin to be better established for some sculptures and, in a few cases, for specific questions relating to provenience to be addressed. The results, when correlated with attributions based on style and early documentation, will serve as a framework for future study of Buddhist limestone and marble sculpture in museum collections worldwide.

Little has been written about the provenience of stone materials used in Buddhist sculpture from China, so preparation of the 2011 exhibition “Echoes of the Past: The Buddhist Cave Temples of Xiangtangshan” at the Smithsonian Institution’s Arthur M. Sackler Gallery in Washington, D.C., provided an excellent opportunity to examine a group of Chinese limestone and marble sculptures currently attributed to Xiangtangshan. These include sculptures on loan from various museums and in the Freer Gallery of Art’s collection. Altogether twenty-five objects were included in the detailed petrographic investigation reported here (Table 1).

The Buddhist cave temple sites at Xiangtangshan have great artistic and historical value. The images in these cave temples include those carved directly into the “living rock” and others that are freestanding, carved either from blocks of local stone or from blocks quarried elsewhere and brought to Xiangtangshan. Unfortunately, many of the sculptures now in museum collections were removed from the cave temples in the early twentieth century,¹ and information about their original locations has been lost. This study, undertaken as the sculptures were prepared for exhibition, was intended to augment art-historical studies aimed at reconstruction and recontextualization of the Xiangtangshan cave temples.

Table 1 • Checklist of Sculptures in Current Study

Object	Original Location at Temple Site	Sample Location
Northern Xiangtangshan: Sculptures Thought to Have Been Integral		
Head of a Buddha, Freer Gallery of Art (F1913.67)	South Cave	Right side of broken neck
Head of Disciple Ananda, Freer Gallery of Art (F1913.134)	South Cave	Rough back near top of head
Kneeling winged monster, Freer Gallery of Art (F1916.345) (see Figure 7)	Middle Cave	Right leg area
Kneeling winged monster, Freer Gallery of Art (F1953.86)	North Cave	Upper area of rough back
Kneeling winged monster, Freer Gallery of Art (F1953.87)	North Cave	Left side
Kneeling winged monster, Freer Gallery of Art (F1977.8)	North Cave	Back on right side
Kneeling winged monster, Freer Gallery of Art (F1977.9)	North Cave	Left side
Head of a bodhisattva attendant of Maitreya, University of Pennsylvania Museum of Archaeology and Anthropology (C353)	North Cave	Right side on rough back
Head of a bodhisattva, University of Pennsylvania Museum of Archaeology and Anthropology (C354)	North Cave	Right side on rough back
Head of a Buddha, possibly Prabhutaratna, Buddha of the Past, Victoria and Albert Museum (A.98-1927)	North Cave	Rough back of head
Northern Xiangtangshan: Freestanding Sculptures		
Seated bodhisattva, Freer Gallery of Art (F1913.57) (see Figure 8)	North Cave	Back bottom edge of base
Seated Buddha, Victoria and Albert Museum (A.4-1924)	North Cave	Back bottom edge of base
Stela, University of Pennsylvania Museum of Archaeology and Anthropology (C429) (see Figure 9)	Unknown location; thought to have been carved at or near Northern Xiangtangshan	Bottom of base
Northern Xiangtangshan (provisional association): Funerary Couch (<i>shichuang</i>)		
Funerary couch base, Freer Gallery of Art (F1915.110) (see Figure 13)	Unknown location; possibly Middle Cave	Central back area near base
Funerary couch cornice, Freer Gallery of Art (F1915.109)	Unknown location; possibly Middle Cave	Rough edge
Funerary couch cornice, Freer Gallery of Art (F1915.336)	Unknown location; possibly Middle Cave	Rough edge
Southern Xiangtangshan: Sculptures Thought to Have Been Integral		
Head of a Buddha, Freer Gallery of Art (1913.135)	Possibly Caves 4–6	Broken surface of neck
<i>Gathering of Buddhas and Bodhisattvas</i> , Freer Gallery of Art (F1921.1)	Cave 2, upper part of west (front) face of central pillar	Upper left edge near repair
<i>Western Paradise of the Buddha Amitabha</i> , Freer Gallery of Art (F1921.2) (see Figure 11)	Cave 2, interior wall above cave temple entrance	Right edge
Southern Xiangtangshan: Freestanding Sculptures		
Standing bodhisattva, Freer Gallery of Art (F1968.45)	Possibly Cave 2	Back of figure in waist area
Standing Bodhisattva Avalokitesvara (Guanyin), University of Pennsylvania Museum of Archaeology and Anthropology (C113)	Cave 2	Bottom of tang
Standing bodhisattva, possibly Mahasthamaprapta, University of Pennsylvania Museum of Archaeology and Anthropology (C150)	Cave 2	Bottom of tang
Standing Pratyekabuddha, University of Pennsylvania Museum of Archaeology and Anthropology (C151)	Possibly Cave 2	Bottom of tang
Standing bodhisattva, Virginia Museum of Fine Arts (56.9.2) (see Figure 12)	Possibly Cave 1	Bottom of tang
Head of Bodhisattva Mahasthamaprapta (Dashizhi), Freer Gallery of Art (F1916.346)	Possibly Caves 4–6	Broken surface of neck

Note: Historical evidence pointing to the origin of these objects from specific locations at the Xiangtangshan sites is given in Wilson and Wang 2010; images and previous citations appear in catalogue entries in Tsiang 2010.

As the majority of sculptures from Xiangtangshan were carved directly into living rock, the first step in this petrographic investigation was to collect and study typical samples of the stone from these sites. Petrographic analysis of limestone entails the systematic description of the four components—framework grains, cements, matrix, and porosity. Marbles are characterized by features such as color, overall texture, primary grain shape, and maximum grain size. Other analytical methods were used as needed, including scanning electron microscopy (SEM) and cathodoluminescence (CL) microscopy. This approach allowed for the proposed sites of origin of the sculptures to be better established and, in some cases, for specific questions about provenience to be addressed.

HISTORICAL BACKGROUND

The Xiangtangshan cave temples in North-Central China (Figure 1) date to the Northern Qi dynasty (550–77) and are known to have contained unsurpassed examples of Buddhist stone sculpture of this period.² The cave temples are located at two principal sites. Northern Xiangtangshan is high on a slope on Gushan (or Drum) Mountain next to the village of Hecun, in Wu'an County, Hebei Province. Its three main caves, referred to as North, Middle, and South, are the largest in scale and the earliest of the Xiangtangshan caves of the Northern Qi. They are associated with the Gao royal family, and the site was a stopping place between the capital Ye and the family base of Jinyang, near present-day Taiyuan, Shanxi Province. Dating is based largely on inscriptions carved in stone at the cave sites and on other historical evidence. An important inscription was found on a stone stela at the site of the Changle Temple, which appears to have been established during the Northern Qi period, or earlier, at the base of Gushan Mountain. The stela itself was carved later, during the Jin dynasty (1115–1234), when many Buddhist caves were repaired and expanded, and it supplies some detailed information on the origins and construction of

the Xiangtangshan caves. The inscription attributes the earliest construction at Northern Xiangtangshan to Emperor Wenxuan, Gao Yang (529–559), the first emperor of the Northern Qi.

Southern Xiangtangshan, sometimes called the Fushan Caves, is about 15 kilometers south-east, near the town of Fengfeng, Henan Province, on the north bank of the Fuyang River. It consists of six caves on two levels—Caves 1 and 2 on the lower level and Caves 3–6 above. An inscription on the carved facade of Cave 2 dates the planning and beginning of construction at the site to 565.

Understanding of these complex sites is still evolving as scholars try to identify when and which sculpted works might have originated there.³ Much of what is known about Chinese

Figure 1 • Map of Northern Qi sites in Hebei and Henan Provinces, from Howard 1996, adapted from *Henansheng gudai jianshu baohu yanjiusuo: Baoshan Lingquansi* (Anyang: Henan wenwu chubanshe, 1991), p. 127, fig. 1

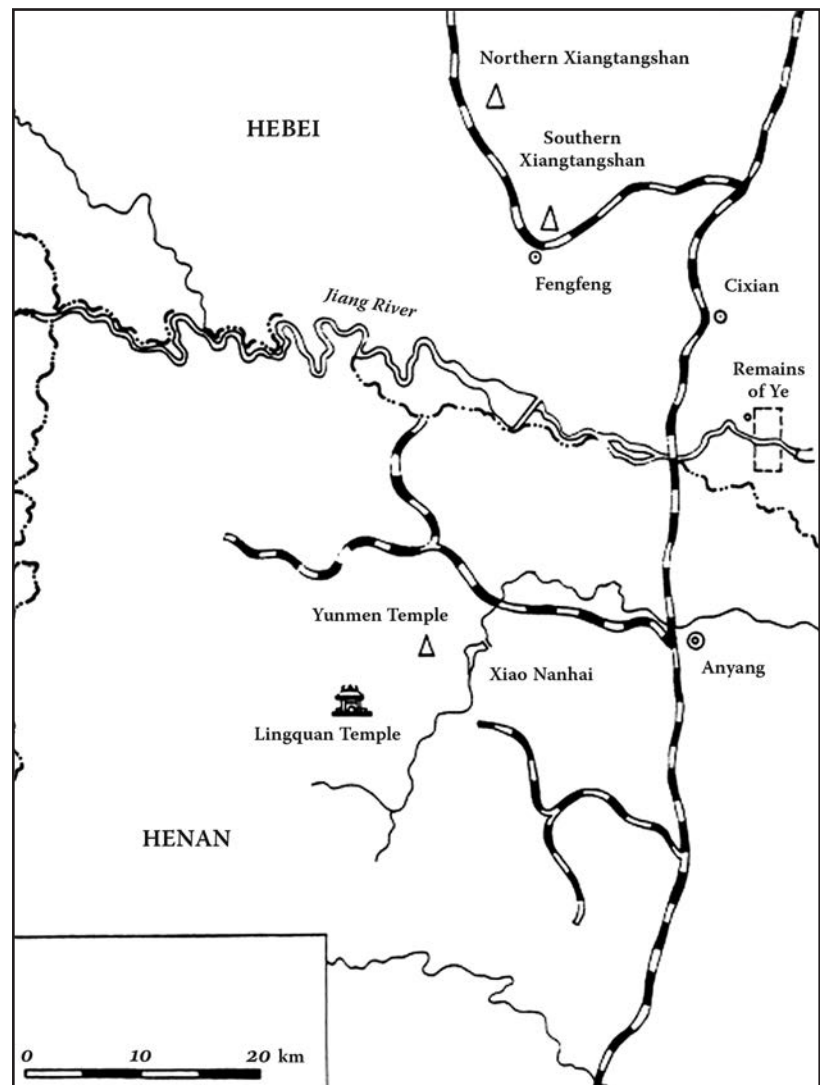




Figure 2 ♦ Exterior of the Buddhist cave temples at Northern Xiangtangshan, Gushan Mountain, Hebei Province

Buddhist cave sites was first recorded between 1909 and 1915 by the French sinologist Édouard Chavannes. His *Mission archéologique dans la Chine septentrionale* (1913–15) includes detailed photographs and descriptions of many Buddhist sites, especially Yungang, Longmen, and Gongxian.⁴ Unfortunately, his book led not only to further scholarly study but also to an interest in collecting Buddhist sculpture. Probably around 1910, sculptures began to be removed from Xiangtangshan, leaving the caves severely damaged. Pieces first appeared on the international art market at that time or shortly thereafter, and C. T. Loo has been recognized as a prominent supplier.⁵ Chavannes

Figure 3 ♦ Exterior of the Buddhist cave temples at Southern Xiangtangshan, Henan Province



did not visit or document either Xiangtangshan site, and the caves there were not surveyed until 1922.⁶ With the publication of Osvald Sirén's *Chinese Sculpture from the Fifth to the Fourteenth Century* in 1925, modern appraisal of the sculptures and the caves from which they presumably came began.⁷

GEOLOGICAL SETTING

Xiangtangshan is located on the North China Platform, which consists of Lower Cambrian to Upper Ordovician strata that were deposited over a large area, extending about 1,500 kilometers east to west and 1,000 kilometers north to south. It is dominated by shallow-water limestones and dolomites of Early Cambrian age, approximately 542 to 513 million years ago. The geologic setting of the Xiangtangshan sites is not well documented, but the limestones there may belong to the Gushan Formation near Handan, Hebei, which consists primarily of late Middle to Late Cambrian tidal-flat limestones and dolomites, some with well-developed paleokarst surfaces.⁸

ANALYTICAL METHODS

Representative limestone samples, 4–10 centimeters long, were obtained from the Buddhist cave temple sites with the cooperation of Zhang Lintang, Office for the Management and Preservation of Cultural Properties, Fengfeng Mining District, Hebei, China. These samples were taken from the natural stone outcrops outside of the cave openings (Figures 2, 3)—either from loose material or from areas already damaged—so as not to cause further degradation of the heavily decorated cave interiors. For this study, thirteen stone samples were taken from each site.

Stone samples were also obtained from sculptures in museum collections traditionally associated with the sites, although these samples were typically much smaller. They were removed from inconspicuous locations, usually in areas of previous loss. Prepared thin sections were analyzed using standard petrographic methods,⁹ and SEM was used to further characterize the textures and the elemental composition of specific

grains, matrix, and naturally precipitated cements. (See the glossary for definitions of these and other technical terms, pages 111–12.)

A pilot study of instrumental neutron activation analysis (INAA)¹⁰ and stable isotope ratio analysis¹¹ was undertaken to determine whether these techniques, which have been applied elsewhere in geological provenience studies of limestone and marble sculpture, would be fruitful in the case of Buddhist sculpture from China. Neither technique was found to be a useful discriminating technique for Xiangtangshan limestones.¹² Selected thin sections were also studied using CL at 15 kV and 0.5 μ A using standard methods.¹³

LIMESTONE CLASSIFICATION

Limestone classification systems based on petrography are well established. The accurate identification of grains, textures, and other features is critical to the systematic naming of carbonate rocks, and for this study the comprehensive atlas-style guide of Scholle and Ulmer-Scholle was an indispensable reference.¹⁴ Four principal components of limestones and related carbonate rocks are: (1) calcareous framework grains of both skeletal and non-skeletal origin, (2) cement, (3) a carbonate or siliciclastic matrix, and (4) primary or secondary pores that tend to occur in carbonate rocks within and/or between framework grains, cement, and matrix.¹⁵

The two most widely used limestone classification systems are those devised by Robert J. Dunham of the Shell Development Company¹⁶ and Robert L. Folk at the University of Texas.¹⁷ Both assign much significance to the presence or absence of matrix and to the texture and composition of framework grains because of their implications in limestone formation, with regard to the depositional environment and subsequent diagenetic changes. The Dunham classification system divides limestones on the basis of whether they are grain-supported or matrix-supported (Table 2). The basic names in the Dunham classification system (grainstone, packstone, wackstone, lime mudstone) can be

modified by qualifying terms based on the petrographic identification of their textural components, which readily provide information on composition and origin. Both the Folk and the Dunham systems have strengths and weaknesses, but the Dunham system tends to be more widely accepted by carbonate petrographers and is used in this study.

DOLOMITIZATION OF LIMESTONES

Limestones are very susceptible to postdepositional alteration, especially recrystallization, with the sum of these processes known as diagenesis. One particularly important diagenetic process is dolomitization, which can take place in a variety of postdepositional environments.¹⁸ By this process, calcite or aragonite, the primary minerals of carbonate sediments, are partly or completely replaced by dolomite, which almost always occurs as a secondary mineral. One reason dolomitization occurs is that aragonite and high-magnesium calcite, having formed via biomineralization to build and maintain the skeletal components of calcareous organisms in the marine environment (e.g., corals, mollusks, echinoderms, calcareous algae), are metastable or unstable both over time and at the higher temperatures and pressures that accompany burial, compaction, and the ultimate lithification of carbonate sediments.¹⁹

Dunham's classification system, published in 1962, referred to recrystallized carbonate rocks simply as "crystalline limestone." Since that time, appreciation and understanding of the diagenetic effects on limestone textures have advanced significantly, and revisions have been proposed by A. F. Embry and J. E. Klován²⁰ and by V. P. Wright.²¹ Wright's expanded classification system proposes using "cementstone" and "sparstone" along with other descriptive subcategories to aid in the identification and classification of carbonate rocks that have recrystallized. He further appreciated the importance of identifying whether the original depositional texture in limestone could be recognized or if it had been completely obliterated

by recrystallization, and if so, whether the recrystallization process had involved dolomitization. His 1992 revision and expansion of the Dunham classification system is important to the work reported herein because some Chinese Buddhist sculptures are carved from limestone that has been moderately to extensively dolomitized.

MARBLE CLASSIFICATION

In this study, all but one of the figures thought to have been freestanding were carved of fine-grained marble of very low metamorphic grade. Thin sections were characterized based on methods adapted by Lorenzo Lazzarini²² and on various studies on ancient marble quarry sources and sculpture incorporating petrographic methods described by Chandra L. Reedy.²³ Characterization is based on features such as color, overall texture, primary grain shape, and maximum grain size. Further analysis by SEM was used to determine grain composition and accessory mineral content.

GEOLOGICAL SAMPLES FROM THE XIANGTANGSHAN CAVE TEMPLE SITES

NORTHERN XIANGTANGSHAN LIMESTONES

Petrographic analysis of the geological samples of limestones from Northern Xiangtangshan shows that they are primarily peloidal oolitic grainstones (Figure 4) that have been partly dolomitized but retain many important details of their original depositional texture. The majority of the framework grains are oolites that range in size from 0.5 to 1.5 millimeters in diameter. Most oolites are oval to irregular in shape with no other particular distinguishing features. Some have a distinct and obvious bioclastic fragment as a core. Also present are larger aggregates, known as grapestones, made up of oolites and other grains bound by an early generation of cement that precipitated shortly after deposition. Other framework grains in these limestones include fragmented bioclastic debris, specifically trilobite, brachiopod,

Table 2 • Limestone Classification System

Fabric Category	Rock Name
Depositional Fabric	
Matrix-supported (clay and silt grade < 62.5 µm)	
< 10% grains	Calci-mudstone (or lime mudstone)
> 10% grains	Wackstone
Grain-supported	
With matrix	Packstone
No matrix	Grainstone
Biological Fabric	
In situ organisms (fossils)	
Encrusting binding organisms	Boundstone
Organisms acted to baffle	Bafflestone
Rigid organisms dominant	Framestone
Diagenetic Fabric	
Nonobliterative	
Main component is cement	Cementstone
Many grain contacts are microstylolites	Condensed grainstone
Most grain contacts are microstylolites	Fitted grainstone
Obliterative	
Crystals > 10 µm	Sparstone
Crystals < 10 µm	Microsparstone

Source: Dunham 1962, adapted by Wright 1992.

pelmatozoan, and bryozoan fragments of varying shapes and sizes, as well as peloids and calcareous clasts up to 4.0 millimeters in length, some with micritized rims.

The primary pore spaces between the framework grains have been completely filled by mosaics of calcite spar that in thin section appear unlike the oolites in morphology as well as in color. Whereas most oolites are pale brown, the calcite spar infill is nearly colorless. Some pores were initially reduced in number and size by precipitation of acicular calcite cement, the texture of which has survived recrystallization.

Postdepositional diagenetic features are common in the Northern Xiangtangshan peloidal oolitic grainstones, particularly the evidence of dolomitization (Figure 5). Many of the oolites have been partly to extensively replaced by small clusters of dolomite rhombs. This replacement was selective, as it appears to have targeted the oolites much more than the calcite spar cement that now fills the intergranular pore spaces. In addition, stylolites and associated solution seams occur in several thin sections of the Northern Xiangtangshan limestones, and they are accentuated by the accumulation of opaque carbonaceous matter and/or other insoluble residues along their paths.

SOUTHERN XIANGTANGSHAN LIMESTONES

The geological samples of limestone from the Southern Xiangtangshan site are primarily sparsely fossiliferous lime mudstones that consist mostly of micrite (Figure 6a). This micrite is calcareous rather than dolomitic, as

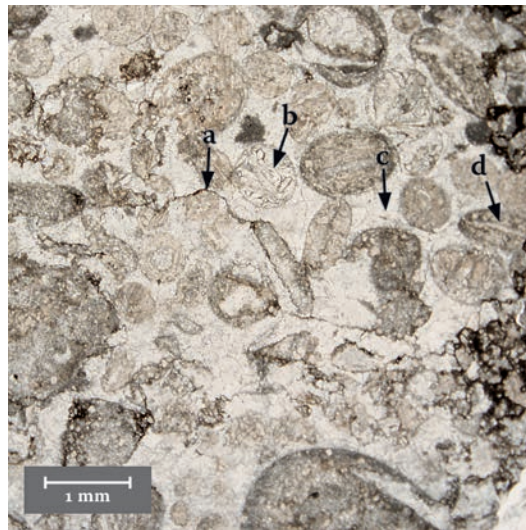
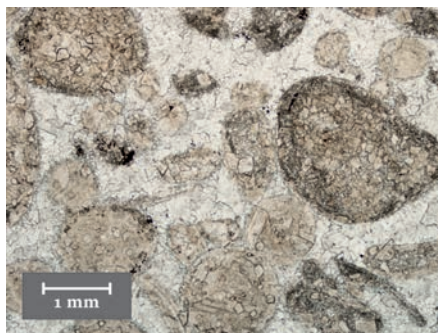


Figure 4 • Peloidal oolitic grainstone from Northern Xiangtangshan (sample NX2), photomicrograph showing typical oolitic texture. Characteristics include: (a) stylolite; (b) dolomitized oolite; (c) calcite spar cement; (d) shell fragment core inside an oolite.

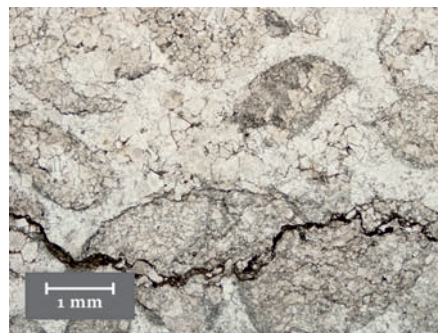
determined by standard staining methods.²⁴ The few framework grains in these lime mudstones from Southern Xiangtangshan are typically bioclasts and rare silt-size quartz grains. The bioclasts include thin, often fragmentary shells of ostracodes, trilobites, and brachiopods. Together, the bioclasts and quartz grains typically make up less than 5 percent of the Southern Xiangtangshan limestone samples.

The most significant nonmicritic component of these mudstones is the very numerous subhedral to euhedral “rice-shaped,” or commonly rhombohedral, crystals of dolomite about 0.01–0.05 millimeters in length (Figure 6b). Generally they occur as isolated grains and occasional clusters in the micrite. Their shape and orientation indicate that they are pseudomorphic, and therefore secondary, after gypsum and anhydrite crystals that nucleated and grew within the original lime mud of the depositional environment. Gypsum and anhydrite

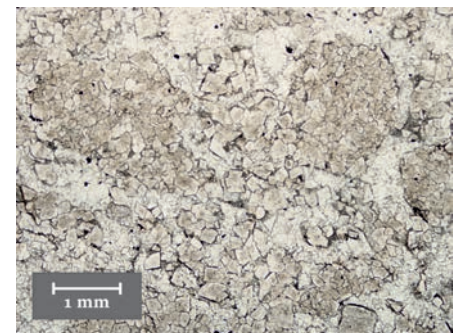
Figure 5 • Limestone from Northern Xiangtangshan (sample NX4), photomicrographs taken in nearby areas in a thin section showing localized effects of dolomitization on its oolitic texture: (a) incipient dolomite formation; (b) approximately 50 percent dolomitization (note stylolite); (c) near-complete dolomitization with oolite ghosts remaining



a

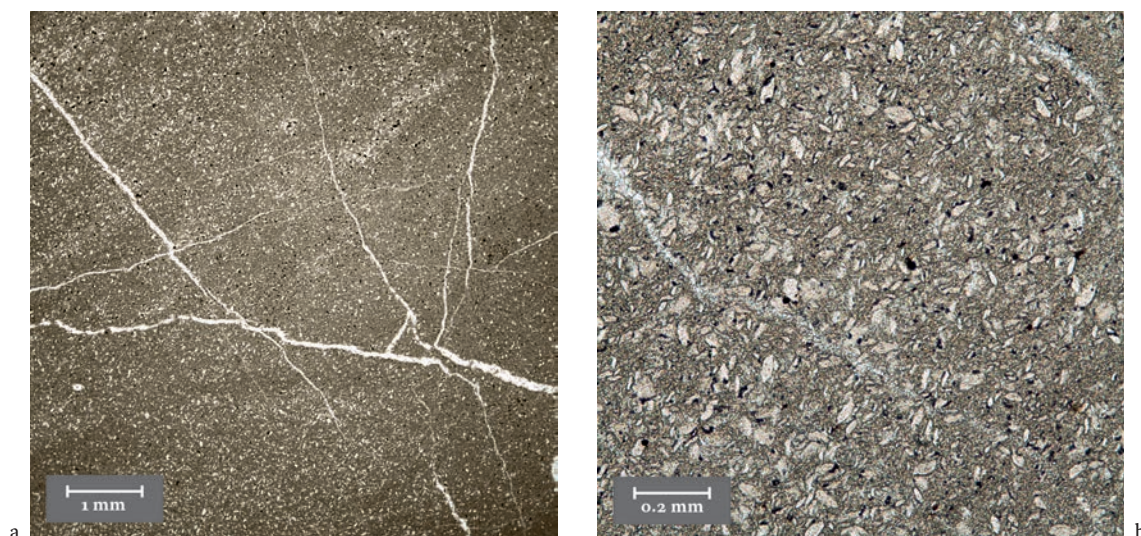


b



c

Figure 6 • Lime mudstone from Southern Xiangtangshan (sample SX2), photomicrographs illustrating: (a) typical fine-grained texture and fractures with calcite spar infill; (b) “rice-grain” texture that is the result of secondary dolomite replacing original gypsum crystals in the depositional environment



are common primary or very early diagenetic minerals in calcareous muds that deposit along modern semiarid to arid coastlines, for example, in the mudflats on the south and southwest coasts of the Persian Gulf,²⁵ and they are also seen in ancient limestones composed of lithified sediments formed in similar depositional environments. As with the lime mudstones from Southern Xiangtangshan, at some time after deposition dolomite formed through pseudomorphic replacement of gypsum and anhydrite.²⁶

The lime mudstones from Southern Xiangtangshan are also finely laminated. In thin section these laminations are delineated by minute compositional and textural differences that reflect varying proportions of small dolomite rhombs and micrite.

Sometime after lithification, the lime mudstone was severely fractured through stresses associated with geologic deformation. As can be seen in Figure 6a, these fractures have been filled by veins of calcite spar. Another important feature seen in many samples is evidence of postdepositional leaching associated with increased porosity. This leaching may be the result of karst processes and/or of limestone dissolution caused by accelerated weathering that is perhaps attributable to air pollution. Both fracturing and postdepositional leaching have led to inherent weakness, which is reflected in the generally poor condition of the

stone outside the entrance to the Southern Xiangtangshan caves.

STONE SAMPLES OF BUDDHIST SCULPTURE ATTRIBUTED TO XIANGTANGSHAN PELOIDAL OOLITIC GRAINSTONES

All ten sculptures thought to have been carved in the living rock in the Northern Xiangtangshan caves are peloidal oolitic grainstones or their dolomitized equivalents. An example is the Freer Gallery’s kneeling winged monster (F1916.345), which appears to have been removed from the right corner of the main altar of the central pillar in the Middle Cave (Figure 7a).²⁷ As seen in the photomicrograph of a thin section (Figure 7b), the limestone consists of irregularly shaped oolites with few peloids, some of which are more than 2 millimeters long. Calcite spar fills the pore spaces between these grains, and some dolomitization has occurred, as evidenced by the clusters of dolomite rhombs throughout the sample.

Among the freestanding statues attributed to Northern Xiangtangshan is a seated bodhisattva in the Freer Gallery (F1913.57; Figure 8a) that is thought to have been placed in a niche in an interior wall of the North Cave. Petrographic study shows that it is carved from a similar, partially dolomitized peloidal oolitic grainstone (Figure 8b). Comparable results were reported for a seated Buddha (A.4-1924)

in the collection of the Victoria and Albert Museum, also thought to be from a wall niche inside the North Cave.²⁸ In both cases, the lithologies are consistent with the geological limestone samples from the Northern Xiangtangshan site, supporting the hypothesis that it was carved from the local stone.

Another important freestanding object, a stela in the University of Pennsylvania Museum of Archaeology and Anthropology (C429; Figure 9a), is thought by some scholars to have been carved at or near Northern Xiangtangshan and placed at an unknown location near Taiyuan, Shanxi Province, about 400 kilometers northwest, during the Northern Qi dynasty. An inscription on the stela includes this passage, “Having obtained from afar precious material from lonely mountain caves and

having consulted the best workers nearby,” which scholars believe refers to Northern Xiangtangshan.²⁹

Petrographic study shows that this stela is carved from a peloidal oolitic grainstone that is again quite similar in texture to the grainstones at Northern Xiangtangshan (Figure 9b), suggesting that it originates from the same geological formation as the grainstones of Northern Xiangtangshan. Furthermore, a macroscopic textural feature known as lenticular bedding links this stela to the native stone of the Northern Xiangtangshan site (Figure 9c), which in some locations is characterized by lenticular bedding (Figure 10). This distinctive type of layering is consistent with sedimentary structures that form in modern arid tidal flats,³⁰ where repeated cycles of quieter, evaporative periods alternate with flooding and where mats of cyanobacteria (blue-green algae) form.

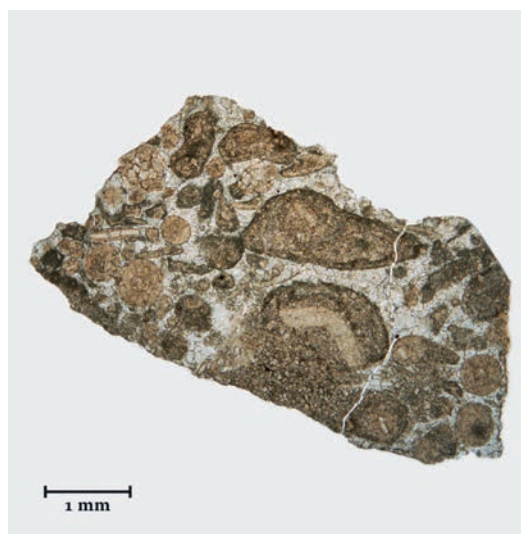
LIME MUDSTONES

Two wall reliefs in the Freer Gallery—*Gathering of Buddhas and Bodhisattvas* (F1921.1) and *Western Paradise of the Buddha Amitabha* (F1921.2; Figure 11a)—are originally from the Southern Xiangtangshan site. *Western Paradise of the Buddha Amitabha* was removed from the exterior wall of Cave 2, just above its entrance, which is now reconstructed

Figure 7 • (a) Kneeling winged monster. China, Hebei Province, Northern Xiangtangshan, Northern Qi dynasty (550–77). Limestone, H. 88.4 cm (34¹/₁₆ in.), W. 47.3 cm (18⁵/₁₆ in.), D. 28.5 cm (11¹/₄ in.). Freer Gallery of Art, Smithsonian Institution, Washington, D.C., Gift of Charles Lang Freer (F1916.345); (b) photomicrograph showing texture of peloidal oolitic grainstone



a



b

Figure 8 • (a) Seated bodhisattva. China, Hebei Province, Northern Xiangtangshan, Northern Qi dynasty (550–77). Limestone, H. 118.0 cm (46½ in.), W. 75.7 cm (29¾ in.), D. 47.3 cm (18¾ in.). Freer Gallery of Art, Smithsonian Institution, Washington, D.C., Gift of Charles Lang Freer (F1913.57); (b) photomicrograph showing texture of peloidal oolitic grainstone

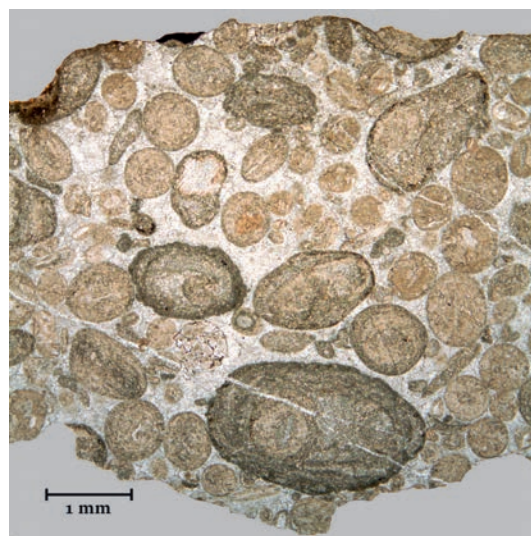


with modern bricks. The limestone is a very fine-grained lime mudstone (Figure 11b) consistent in texture with samples from outside the caves at Southern Xiangtangshan. Few framework grains are present, and the rare bioclasts are fragmentary. The matrix contains numerous “rice-shaped” crystals of secondary dolomite. Like the geological samples, this lime mudstone is also heavily fractured, with the fissures now filled by calcite spar.

MARBLES

Six freestanding figures listed in Table 1, including a head of Bodhisattva Mahasthmaprapta (Dashizhi) (Freer Gallery of Art, F1916.346) thought to be from a standing figure, constitute a significant assemblage of freestanding sculpture traditionally attributed to Southern Xiangtangshan. With the possible exception of the bodhisattva head,³¹ all were found to be composed of a similar fine-grained marble. These sculptures have the outward appearance of limestone, with fine layering that appears to be sedimentary in origin, and several had been previously identified as limestone in museum records. The metamorphic grade of this stone is sufficiently low that it would also be correct to classify it as a sedimentary rock, a recrystallized limestone called sparstone in Wright’s amended Dunham classification scheme, but herein the stone is classified as fine-grained marble.

The primary sedimentary texture of this marble has been largely obliterated through recrystallization. The stone is calcite-rich with minor amounts of rhombohedral dolomite, and minor accessory euhedral pyrite was observed in most thin sections. Calcite crystal boundaries tend to be curved or embayed, although straight and occasional sutured boundaries were also observed. The maximum grain size in the individual specimens falls between 0.88 and 1.60 millimeters.³² The marble has a mosaic



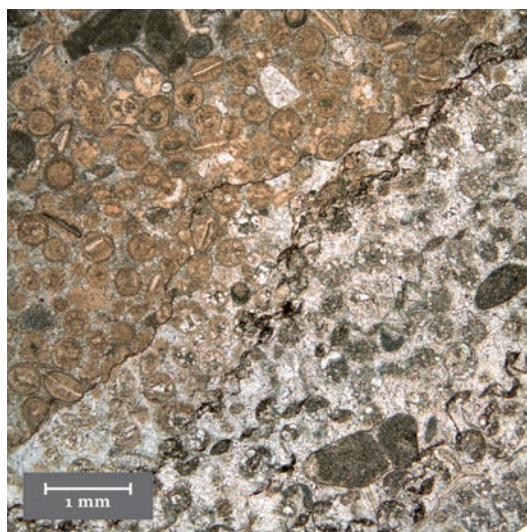


Figure 9 • (a) Stela. Provenience unknown, Northern Qi dynasty (550–77), dated 575. Limestone, H. 213.5 cm (84 in.), W. 25.5 cm (10 in.), D. 62.0 cm (24 3/4 in.). University of Pennsylvania Museum of Archaeology and Anthropology (C429); (b) photomicrograph showing texture of peloidal oolitic grainstone; (c) detail of base (obverse) with lenticular bedding

texture, with a fabric that ranges from heteroblastic to homeoblastic. Occasional fine stylolites are present.

An example of this marble is the Virginia Museum of Fine Arts' standing bodhisattva (56.9.2; Figure 12a). In thin section, this fine-grained stone is seen to be composed of a grayish mosaic of calcite crystals on average 0.60 millimeters in length, with minor rhombohedral crystals of dolomite (Figure 12b). The texture is oblitative with no remaining evidence of its prediagenetic appearance. No outlines of oolites, bioclasts, or mineralogically distinct domains remain that might allow for reconstruction of the depositional and early diagenetic history. The texture and composition of the fine-grained marble are dissimilar to those seen in other dolomitized or otherwise recrystallized limestones of Northern and Southern Xiangtangshan, which usually retain important clues to their original character, as described above.

Figure 10 • Life-size “impression” of the Buddha’s hand on the south exterior wall at Northern Xiangtangshan, polished smooth intentionally or through wear, revealing characteristic lenticular bedding

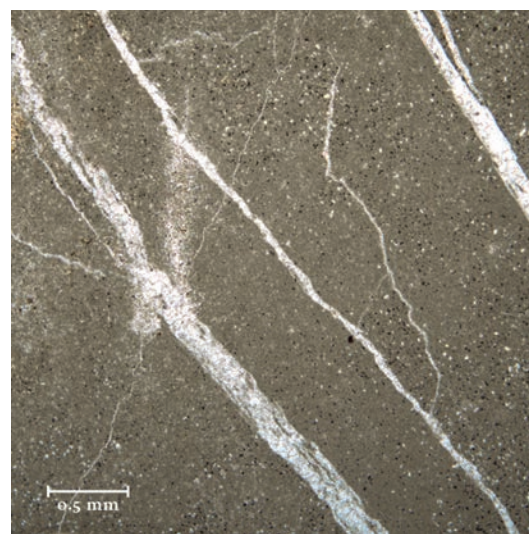


Figure 11 • (a) Detail of *Western Paradise of the Buddha Amitabha*. China, Henan Province, Southern Xiangtangshan, Northern Qi dynasty (550–77). Limestone, H. 159.3 cm (62¾ in.), W. 334.5 cm (131½ in.). Freer Gallery of Art, Smithsonian Institution, Washington, D.C., Gift of Charles Lang Freer (F1921.2); (b) photomicrograph showing fine-grained, thinly laminated texture of mudstone with calcite spar-filled fractures

The remaining standing figures display similar petrographic characteristics, suggesting they might have been carved from a similar or the same marble. The stone is quite unlike the heavily fractured lime mudstone of Southern Xiangtangshan, which may have been unsuitable for creating three-dimensional sculpture. The Virginia Museum’s standing bodhisattva is also important because it shows some of the strongest evidence that these figures were

freestanding rather than carved into the living rock, as some researchers have suggested. Whereas most of the figures have a rough-hewn back that could be interpreted as the coarse surface left after clandestine removal from a cave wall, the back of the standing bodhisattva (Figure 12c) is coated with a well-developed flowstone deposit of chemically precipitated calcite that forms when water flows through a cave. Similar but less-developed deposits can be seen on most of the other figures, supporting the hypothesis that they, as well, were carved in the round.

A second significant subgroup of sculpture in the Freer Gallery carved from fine-grained marble includes a funerary couch base (F1915.110) and two cornices (F1915.109, F1915.336), thought to be elements of a single couch (*shichuang*) with both Central Asian and Chinese Buddhist motifs. Following initial research undertaken by the Museum für Ostasiatische Kunst in Cologne in the early 1970s, a possible connection to Xiangtangshan was proposed.³³ A more recent evaluation of the historical and stylistic evidence has suggested that these fragments come from the funerary couch that was in a niche in the Middle Cave of Northern Xiangtangshan.³⁴ Whereas ongoing research of these three elements as well another five in other museum collections supports the theory that they originally were part of the same couch, its association with Northern Xiangtangshan



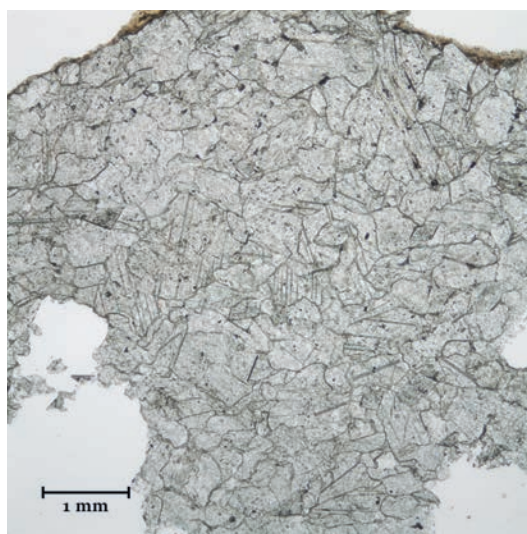


a

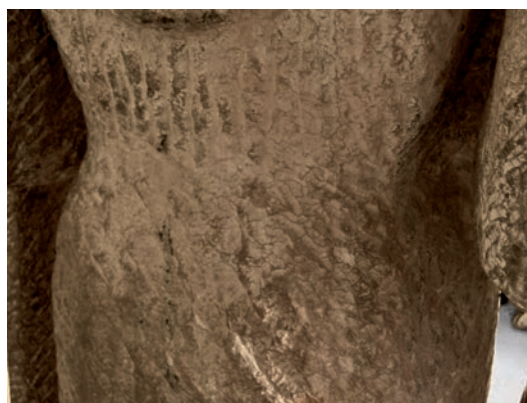
remains to be established. Regardless, the petrographic examination of the stone material of these objects is of interest here.

Figure 13 shows the funerary couch base (F1915.110) along with a photomicrograph demonstrating that it is a fine-grained marble. Thin sections from the cornices show features similar to the funerary couch base, supporting other evidence that the three pieces were carved from the same type of stone, possibly from the same quarry. Yet neither the free-standing figures nor the funerary couch elements were carved from the limestone characteristic of the Xiangtangshan caves from which they are said to have originated. The evidence indicates that these objects were worked from stone obtained from a geological source other than the Xiangtangshan sites, but we currently do not know whether they were carved there or at a different location. The similarity of the

Figure 12 • (a) Standing bodhisattva. China, Henan Province, Southern Xiangtangshan, Northern Qi dynasty (550–77). H. 170.1 cm (67 in.), W. 41.9 cm (16½ in.), D. 28.0 cm (11 in.). Virginia Museum of Fine Arts, Richmond, Adolph D. and Wilkins C. Williams Fund (56.9.2); (b) thin section that displays the texture of a fine-grained marble, although the sculpture is described as limestone in museum records; (c) detail of reverse showing flowstone deposit from the cave environment



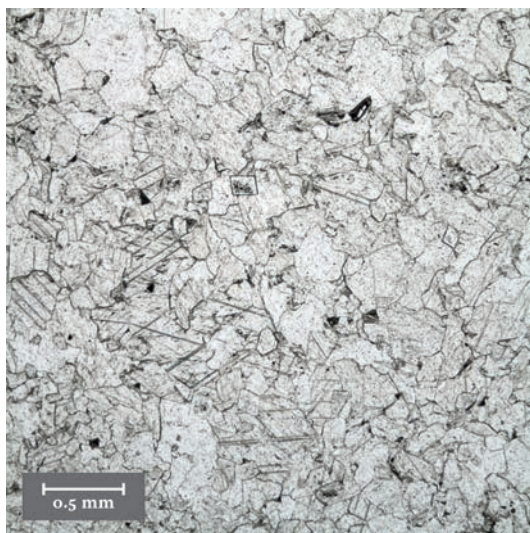
b



c



Figure 13 • (a) Funerary couch base. China, possibly Northern Xiangtangshan, Northern Qi dynasty (550–77). Gray marble, H. 60.3 cm (23¾ in.), W. 234.0 cm (92½ in.), D. 23.5 cm (9¼ in.). Freer Gallery of Art, Smithsonian Institution, Washington, D.C., Gift of Charles Lang Freer (F1915.110); (b) photomicrograph showing fine-grained texture



fine-grained marble in the standing figures and the elements of the funerary couch suggest a common provenience of the marble itself, a possible connection that deserves to be explored.

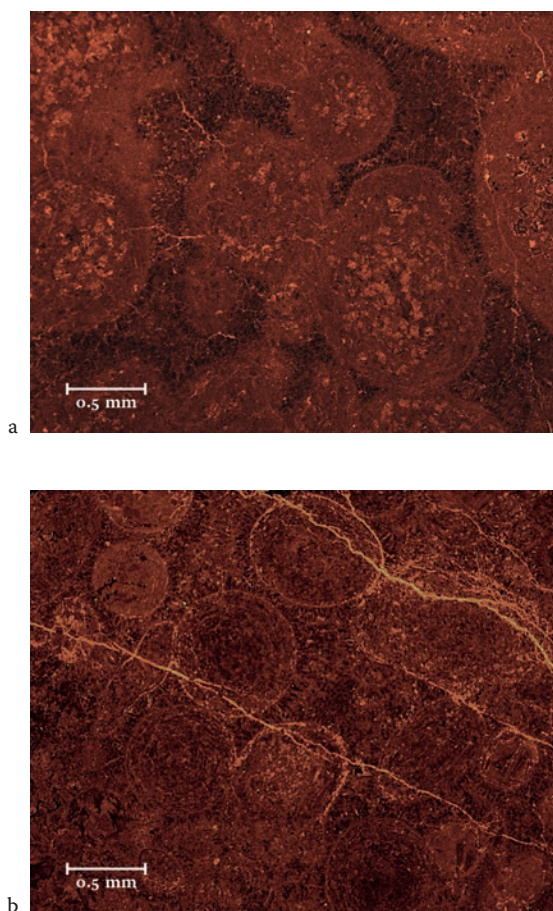
ANALYSIS BY CATHODOLUMINESCENCE MICROSCOPY

Cathodoluminescence (CL) microscopy is an imaging technique for examining thin sections using an optical microscope with a CL-stage attachment. CL emission is achieved by bombarding a material with an electron beam from a cathode ray tube. Emissions from some minerals reveal textures and compositional variations that are not otherwise evident with visible light. Carbonate minerals such as calcite and dolomite, when thus exposed, emit visible light at wavelengths reflecting the presence of impurities within their crystal structure that can be used to recognize differences in trace

elemental composition. CL microscopy allows spatial variations to be recorded and is a reliable discriminant technique that can be rapidly performed.

Selected samples from both temple caves and the sculptures were studied using CL microscopy to determine whether this technique could yield further information that might help identify and differentiate the limestones from one another. In carbonates, manganese (Mn^{2+}) is often a main activator of CL emission. In calcite and dolomite, manganese tends to produce orange and red emissions, respectively, at around 620 and 660 nanometers. Other colors can occur depending on the presence of additional trace element activators, such as rare earth elements, or other factors, such as crystal growth kinetics. In general, trace amounts of iron (ferrous, Fe^{2+} , and ferric, Fe^{3+}) act to dampen or completely quench the CL signal. Some experimental evidence suggests that for carbonate minerals, the color of the CL and its intensity are controlled primarily by the ratio of iron to manganese rather than by the absolute concentrations of either Fe or Mn cations.³⁵

For all the limestones examined here, the CL images show textures similar to those observed in the petrographic study (Figures 14, 15). The framework grains, which are primarily oolites and peloids in the Northern Xiangtangshan samples, and a few bioclasts and secondary dolomite crystals pseudomorphic after gypsum in the Southern Xiangtangshan samples, tend to be bright orange-red when imaged using CL microscopy. This finding suggests that they are richer in Mn^{2+} than the cements



activator is present, and the calcite is darker due to the quenching effect of iron. This feature was observed consistently on all of the marble samples, a finding that may point to the same or similar geological sources for the standing figures and the funerary couch components.

CL microscopy provided textural information similar to that found using petrography but also contributed compositional data. In every case, the results of the CL microscopy strengthened the proposed correlations between samples obtained from sculptures and those obtained from geological materials from the cave sites.

The present study pioneers the use of petrographic methods for characterizing stone materials used in Chinese Buddhist sculpture and explores their suitability in this context. Problems with identification, characterization, and differentiation invariably arise with

Figure 14 • Cathodoluminescence images of thin sections from peloidal oolitic grainstones from Northern Xiangtangshan: (a) site sample NX2; (b) seated bodhisattva (F1913.57). Most of the oolites are primary dolomite that appears medium orange-red; secondary dolomite rhombs are bright orange-red (often zoned); most of the natural cement is Fe-rich and darker than the oolites; minor amounts of interstitial cement are medium orange; late-stage pore-filling calcite spar cement is yellow.

in the limestones from both sites, which are darker and therefore likely to be more Fe-rich. Compositions of these framework grains and of the dolomite pseudomorphs were verified through semiquantitative elemental analyses of samples with an energy dispersive X-ray analyzer in a scanning electron microscope. The Ca to Mg ratio was determined on a number of grains using this method, and the average value for calcite was found to be 97 to 3, and for dolomite, 58 to 42. The latter values given for dolomite are close to the rarely occurring stoichiometric ratio of 50 to 50.³⁶

Of particular note are CL photomicrographs of the fine-grained marble samples of the standing figures and the components of the funerary couch (Figure 16). Most of those images show a dark reddish color, with euhedral crystals of dolomite that luminesce a bright orange to orange-red. Here, as well, the dolomite probably is bright because a Mn^{2+}

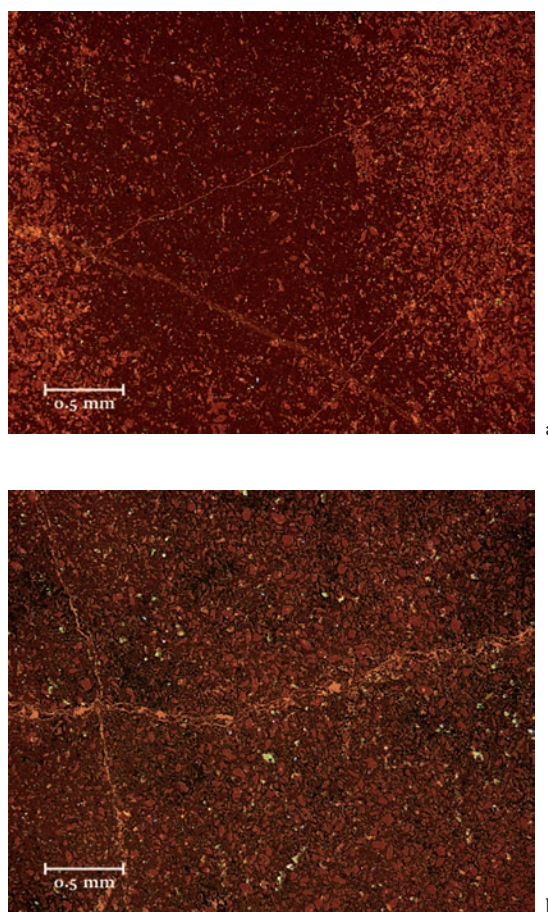
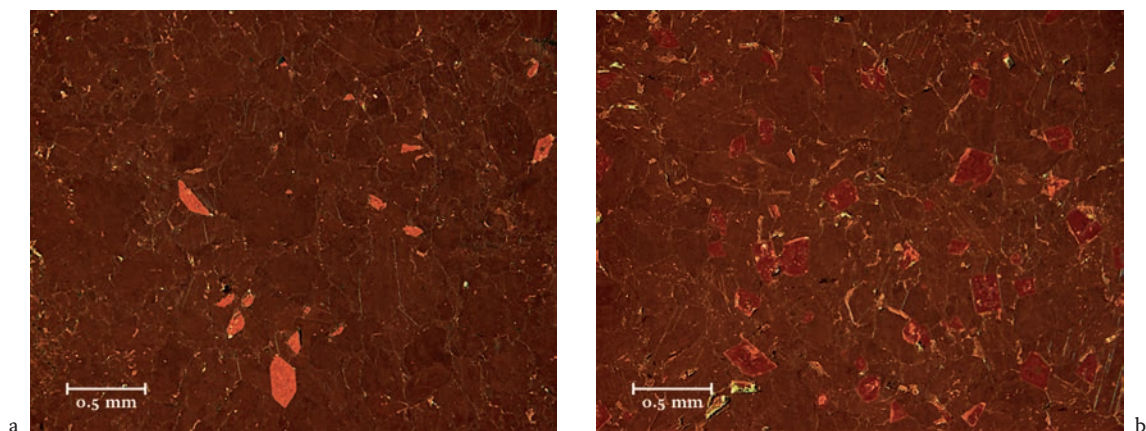


Figure 15 • Cathodoluminescence images of thin sections from lime mudstones from Southern Xiangtangshan: (a) site sample SX9; (b) *Western Paradise of the Buddha Amitabha* (F1921.2). The dolomite crystals were formed through pseudomorphic replacement of gypsum and appear medium to bright orange-red; fine-grained Fe-rich micrite is dark; late-stage pore-filling calcite cement is yellow.



limestones that are pervasively recrystallized or dolomitized, and analytical methods that involve chemical analysis are therefore problematic. For limestones that exhibit pervasive diagenetic changes, as well as the effects of weathering, petrographic analysis proved to be the best characterization method. By establishing a petrographic basis for the characterization of limestones from the cave temples of Northern and Southern Xiangtangshan, this study can serve as a guide for future investigations of Chinese Buddhist sculptures in museums worldwide. The approach taken in this study can be used as a first step in all studies of provenience of stone sculpture and has the potential to become the norm for more meaningful comparisons in the future.

Petrography allows for the comprehensive characterization of limestones, and it has shown that exceptional agreement exists between limestone collected from the cave temple sites and Buddhist sculptures in museum collections. At Northern Xiangtangshan, the native peloidal oolitic grainstone was used for sculpture carved in the living rock as well as for the freestanding seated Buddha figures that were placed in the niches in North Cave. The freestanding stela thought to have been carved at Northern Xiangtangshan also shares petrographic and textural features with the grainstones from this site. (For a discussion of comparable oolitic limestones from Longmen, another important Buddhist cave temple complex, see Appendix 1, pages 110–11.)

The native limestone at Southern Xiangtangshan is a lime mudstone that is heavily fractured and partially recemented with numerous veins of calcite spar. Both wall reliefs in the Freer Gallery are carved from this distinctive fractured limestone.

The marble used for several freestanding sculptures in this study originates from a geological source quite different from those at the Northern or Southern Xiangtangshan sites. Their provenience remains undetermined at present, but additional sampling and further petrographic analyses may help to shed more light on this topic. The same holds true for the funerary couch base and cornices, which are also carved from fine-grained marble and thus could have an origin similar to that of the freestanding sculptures.

As an analytical method, CL microscopy was found to be an excellent complement to petrography. It helps confirm the compositional and textural features of limestones and marbles and, in particular, was found useful in the detailed characterization of natural cements. This investigation advances understanding of sculpture from Xiangtangshan and offers valuable support to the ongoing art-historical studies on Buddhist sculpture from China.

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Figure 16 • Cathodoluminescence images of freestanding objects, fine-grained marbles: (a) standing bodhisattva (F1968.45); (b) funerary couch base (F1915.110). Most of each sample is an idiomorphic mosaic composed primarily of euhedral Fe-rich calcite crystals that appear dark; the euhedral Mn-rich dolomite grains are brighter orange-red; small amounts of pore-filling calcite spar are yellow.

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NOTES

- 1 Wilson and Wang 2010.
- 2 The most recent research on the historical context of Xiangtangshan and its sculpture is summarized in Tsiang 2010, pp. 18–22.

- 3 Wilson and Wang 2010.
- 4 Chavannes 1913; Chavannes 1915.
- 5 Wilson and Wang 2010. The art dealer C. T. Loo was the single most important source of works taken from the Xiangtangshan sites. Loo mentions in the preface to his 1940 sales catalogue that he sold a bodhisattva head from Xiangtangshan to a French dealer in 1909 or 1910 (Loo 1940, unpagged).
- 6 The first detailed survey of Xiangtangshan was started in 1922 and published in Tokiwa and Sekino 1925–38; English translation Tokiwa and Sekino 1926–38, vol. 3, text, pp. 41–58.
- 7 Sirén 1925.
- 8 Meng, Ge, and Tucker 1997, pp. 190–92.
- 9 Standard thin sections having a thickness of about 30 micrometers were prepared by Spectrum Petrographics, Vancouver, Washington.
- 10 Blackman and Bishop 2007; Matthews 1997; Meyers and van Zelst 1997; Holmes and Harbottle 1994a; Holmes and Harbottle 1994b.
- 11 Attanasio, Brilli, and Bruno 2008.
- 12 The pilot study included nine samples from Northern Xiangtangshan, six from Southern Xiangtangshan, and thirteen from sculptures in the Freer Gallery. One hundred milligrams were taken for analysis from homogenized drilled powder samples each weighing approximately 1 gram. Initial results of this study showed overlapping fields of compositional and isotopic data, presumably attributable to chemical changes that result from some combination of stone weathering and postdepositional diagenetic changes, which are severe on the cave exteriors, as well as pervasive dolomitization of some samples, which is common in ancient carbonates dating to the Ordovician and Cambrian periods. The overall lack of diversity in chemical elements typically present in carbonate rocks as compared with siliciclastic mudrocks may be another contributing factor (Taylor and McLennan 1985).
- 13 Marshall 1988, esp. pp. 76–93.
- 14 Scholle and Ulmer-Scholle 2003.
- 15 Tucker and Wright 1990, pp. 1–27.
- 16 Dunham 1962; Wright 1992.
- 17 Folk 1974.
- 18 Machel and Mountjoy 1986.
- 19 Tucker and Wright 1990.
- 20 Embry and Klován 1971.
- 21 Wright 1992.
- 22 Lazzarini 2004.
- 23 Reedy 2008, pp. 87–96.
- 24 Dickson 1965. The staining method described by Dickson allows for differentiation of iron-poor and iron-rich calcite, and dolomite. Nonferroan calcite accepts a pink stain; ferroan calcite takes a mauve to light purple stain; nonferroan dolomite does not stain; and ferroan dolomite takes a greenish-blue to blue stain, depending on iron content.
- 25 Al-Sharhan and Kendall 2003.
- 26 Scholle and Ulmer-Scholle 2003.
- 27 The kneeling winged monster is one of two originally located on opposite sides of the central pillar in the Middle Cave at Northern Xiangtangshan. Whereas the companion figure appears to have been carved directly in the stone and is largely intact today, the Freer Gallery's monster was probably created separately and set into position during the Northern Qi

- dynasty. A large fracture that runs through the cave interior in the monster's former location suggests that the quality of some of the stone in this area may not have been suitable for carving, thereby prompting installation of a freestanding figure (Tsiang 2010, p. 191).
- 28 The seated Buddha was studied by petrographic methods as reported in R. W. Sanderson, British Museum (Natural History), Geological Museum, London, to John Larson, Sculpture Conservation Department, Victoria and Albert Museum, London, May 20, 1988. Sanderson describes the limestone as a "recrystallized, brownish gray limestone, probably originally an oopelsparite" and documents a mosaic of calcite spar, with ghosts of rounded masses up to about 0.7 millimeters in length. Although the letter does not include photomicrographs, this description indicates that the sample is similar to the peloidal oolitic grainstones from Northern Xiangtangshan.
 - 29 Quoted in Tsiang 2010, p. 233.
 - 30 Collinson, Mountney, and Thompson 2006.
 - 31 Petrographic analysis of the small sample from the bodhisattva head (F1916.346) was inconclusive, but it is consistent in appearance with an extremely weathered area on the marble standing bodhisattva in the University of Pennsylvania Museum of Archaeology and Anthropology (C150).
 - 32 Lazzarini 2004. A maximum grain size of 2 millimeters roughly separates fine-grained marble from medium-grained varieties.
 - 33 Gabbert 1972, pp. 279–85, 414–17. In the files of the Museum für Ostasiatische Kunst, Cologne, is a handwritten comment in the inventory log of 1932–39 by the museum's director, Frieda Fischer, noting a communication from James Mellon Menzies, a professor at the Shandong Christian University, China, stating that he had seen the intact funerary couch in a burial chamber in one of the Northern Xiangtangshan caves. Discussion of the site as a burial place continues today, but no further evidence establishing that the funerary couch was situated at Northern Xiangtangshan has come to light.
 - 34 Priewe 2009.
 - 35 Frank, Carpenter, and Oglesby 1982.
 - 36 Tucker and Wright 1990, p. 370.

APPENDIX 1

LIMESTONES FROM THE LONGMEN CAVE TEMPLE SITE

The Buddhist cave temple site of Longmen, encompassing about 1,400 caves, is near the city of Luoyang, Henan Province, approximately 250 kilometers southwest of the Xiangtangshan sites. Although Longmen is not the focus of this article, it seems worthwhile to briefly discuss some limestone samples obtained from that site because they exhibit some similarities to those from Northern Xiangtangshan. Like the latter, the limestones from Longmen are largely oolitic grainstones. Nonetheless, some

important differences in their petrographic characteristics are becoming evident.

Preliminary examination of several limestone samples from Longmen showed that some of their oolites have been appreciably dolomitized (Figure App. 1.1). The oolites in these samples are circular to slightly elliptical in shape and fairly uniform in size. A distinct concentric fabric outlines the original cortices of some of the Longmen oolites, and some have nuclei of unidentifiable micritized grains. Peloids are rare.

Other framework grains in the Longmen limestones include curved, micritized fragments, perhaps of ostracode shells. A few peloids, trilobite and brachiopod fragments, and rare echinoderm fragments identifiable by their characteristic syntaxial overgrowths constitute the remaining framework grains. Most of the framework has dolomitized to some degree, but the grains are still recognizable from their distinct shapes and textures. Rare pyritized grains are also present.

The original pore spaces are reduced in size and number by calcite spar infill, which has been variably dolomitized and recrystallized, as shown by the abundance of euhedral to subhedral dolomite rhombs. The dolomite has selectively replaced the original carbonate minerals that constituted the oolites and other framework grains, as well as the original pore-reducing cement. Occasional stylolites are also present.

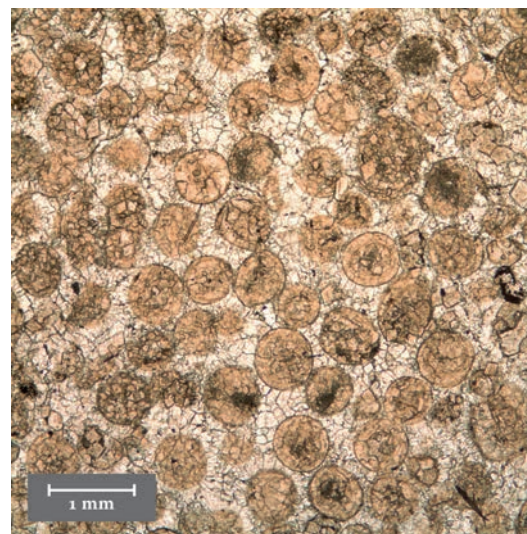


Figure App. 1.1 • Oolitic grainstone from the cave temple site of Longmen, Henan Province (sample L15), photomicrograph showing relatively small oolites (around 0.34 mm in diameter), which are of more uniform size than those found in the limestones of Northern Xiangtangshan

Table App. 1.1 • Oolite Size and Sorting in Geological Samples from the Northern Xiangtangshan (NX) and Longmen (L) Cave Temples

Sample	Mean (mm)	Median (mm)	Sorting (σ)
NX3, n = 37	0.54	0.57	0.78
NX7, n = 108	0.49	0.51	0.76
L14, n = 31	0.35	0.35	0.25
L16, n = 22	0.32	0.34	0.34
L17, n = 31	0.36	0.36	0.18

In marked contrast to these oolitic grainstones, other Longmen samples are sparstones or dolosparstones with oblitative fabrics that are primarily idiotopic in character,¹ a texture that may be the result of an episode of pervasive dolomitization and recrystallization. The individual dolomite crystals range in length from 0.30 to 0.60 millimeters.

Although oolitic grainstones occur at both Northern Xiangtangshan and Longmen, this limited comparative study suggests they are distinguished by measurable differences in the size and distribution of the oolites. As shown in Table App. 1.1 and in photomicrographs of these limestones, the Northern Xiangtangshan oolites tend to be larger and more varied in shape, with an average diameter of 0.51 millimeters and with a sorting of around 0.77. By contrast, the Longmen oolites are generally smaller, about 0.34 millimeters in diameter, and of a more uniform size, with a sorting of around 0.26. Oolites from the Northern Xiangtangshan site tend to be more elliptical and irregularly shaped as compared to the more spherical Longmen oolites.

Given the considerable size of the Longmen site and the small number of samples in the current study, future research is necessary to more precisely characterize the varieties of limestones that occur there.

NOTE

¹ Sibley and Gregg 1987.

GLOSSARY OF GEOLOGICAL TERMS

acicular. A crystal habit characterized by a radiating mass of slender, needlelike crystals.

anhydrite. A mineral composed of anhydrous calcium sulfate (CaSO_4).

aragonite. One of two common minerals composed of calcium carbonate (CaCO_3) usually found in limestone.

bioclast. Clast of skeletal (biological) origin.

calcareous. Formed from or containing a high proportion of calcium carbonate (CaCO_3) in the form of calcite or aragonite.

calcite. Mineral composed of calcium carbonate (CaCO_3) found in marble, limestone, chalk, etc.

calcite spar. Coarse crystalline cement that fills pore spaces in many limestones. Calcite spar forms by precipitation from carbonate-rich solutions passing through pore spaces in the sediment. It consists of minute vein- or pore-filling crystals that increase in size toward the cavity center. It is coarser than micrite and in thin section can be distinguished by its clarity and crystallinity.

carbonate rock. Rock composed of carbonate minerals, especially limestone and dolomite.

cement. Pore-filling crystals that act to bind grains.

clast. Fragment of an at least partially lithified carbonate sediment that has been transported and redeposited.

compaction. Diagenetic process that involves both physical and chemical changes leading to loss of water and pore space.

diagenesis. Chemical, physical, or biological changes undergone by sediments after initial deposition and during and after lithification, exclusive of surface alteration (weathering) and metamorphism.

dolomite. Mineral composed of calcium magnesium carbonate [$\text{CaMg}(\text{CO}_3)_2$].

dolomitization. Process by which limestone is altered to dolomite. When limestone comes in contact with magnesium-rich water, the dolomite replaces the calcite, volume for volume. Dolomitization involves recrystallization and therefore causes obliteration of original sedimentary texture.

euheral. Characterized by well-crystallized faces.

fabric. Spatial and geometric configuration of all elements that constitute a rock, which are usually related to the directional orientation of its grains. A rock's fabric is typically on a larger scale than its texture.

framework grain. Detrital component of sedimentary rock of either skeletal or nonskeletal origin, typically up to about 2 millimeters in diameter.

- grain-supported.** Descriptor to indicate the dominance of framework grains in a limestone.
- grapestone.** Aggregate of a small number of recognizable grains cemented together by micrite or calcite spar.
- gypsum.** Mineral composed of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).
- heteroblastic.** Characterized by a nonuniform mosaic of calcite crystals of varying grain size.
- homeoblastic.** Characterized by an equidimensional mosaic of calcite grains, typically with straight and gently curved boundaries.
- idiotopic.** Descriptor of a carbonate texture in which most crystals are euhedral.
- karst.** Terrain, generally underlain by limestone or dolomite, in which the topography is chiefly formed by rock dissolution and may be characterized by sinkholes, closed depressions, subterranean drainage, and caves.
- lenticular bedding.** Primary sedimentary structure of lens-shaped layers that form in tidal and delta front depositional environments with waters fluctuating between high and low energy. When lenticular bedding occurs in limestones it typically consists of alternating layers of dark gray calcite-rich limestone and light brown dolomite-rich limestone.
- limestone.** Sedimentary rock consisting primarily of calcium carbonate (CaCO_3).
- lithification.** Various processes whereby sediments are converted into stone.
- marble.** Metamorphosed limestone composed mainly of recrystallized calcite with dolomite.
- matrix.** Very fine carbonate or siliciclastic sediment typically less than 62 microns in diameter.
- matrix-supported.** Descriptor to indicate the predominance of microscopic carbonate or siliciclastic sediment in a limestone.
- metamorphic grade.** Measure of the relative intensity of metamorphism undergone by a specimen. In general, the presence of mineral assemblages stable at progressively higher pressures and temperatures indicates a higher metamorphic grade.
- micrite.** Dense, fine-grained carbonate mud (or microcrystalline calcite) with particles usually less than 5 microns in size; sometimes refers to rocks composed of mud formed by erosion of larger carbonate grains or by precipitation of organic materials.
- micritization.** Precipitation of micrite resulting from the degradation of skeletal carbonate particles by cyanobacteria (blue-green algae).
- nonskeletal.** Framework grains derived primarily from nonbiological processes.
- oolite** (also called *oid*). Coated grain with a calcareous cortex that typically has concentric layers and a nucleolus of variable composition. Oolites tend to be spherical or elliptical and less than 2 millimeters in diameter.
- peloid** (also called *pellet*). Sand-size framework grain (0.6 to 2.0 millimeters) composed of micrite; one of the four common framework grains in carbonate rocks (the others are bioclasts, intraclasts, and oolites). Peloids can be rounded or subrounded to irregular in shape and are internally structureless. They are either fecal pellets of marine invertebrates or carbonate grains that have been so significantly altered by micritization that their structure and origin are no longer recognizable.
- pseudomorph.** A mineral that substitutes for another through replacement while the general shape and dimensions remain unchanged.
- recrystallization.** Diagenetic process causing changes in the crystal fabric of a mineral while its species remains the same.
- siliciclastic.** Descriptor of noncarbonate sediment or rock that is composed almost exclusively of quartz or other silicate minerals.
- skeletal.** Derived from organisms that produce calcareous skeletons.
- stylolite.** Irregular discontinuity or nonstructural fracture in limestones and other sedimentary rocks. Stylolites result from compaction and pressure dissolution during diagenesis.
- syntaxial overgrowth.** A crystallographically oriented overgrowth of a mineral on a substrate of the same chemical composition.
- texture.** Relationship between component particles or crystals of a rock and their geometric aspects, such as size, shape, and sorting.

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PICTURE CREDITS

Department of Conservation and Scientific Research, Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, D.C.: 2-6, 7b, 8b, 9b, 9c, 10, 11b, 12b, 12c, 13b, 14, 15, 16, App. 1.1

Freer Gallery of Art, Smithsonian Institution, Washington, D.C.: Figures 7a, 8a, 11a, 13a

Travis Fullerton, Virginia Museum of Fine Arts, Richmond: Figure 12a

University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia: Figure 9a

北齐响堂山佛教石窟雕像石材的岩相学分析

摘要

中国中北部的响堂山是一个重要的佛教石窟寺群，其年代可追溯到北齐时代（550-77）。北响堂山和南响堂山的洞穴内都曾刻有石雕，但自二十世纪初以来，石雕逐渐佚失，现多由世界各地的公共机构和私人所收藏。2011年名为“历史的回响：响堂山佛寺石窟”的展览，为收藏于弗利尔美术馆的响堂山石雕以及来自其他博物馆的相关收藏提供了一个绝佳的研究机会。本项研究首先对来自南响堂山和北响堂山洞穴外部的石灰岩样品进行了岩相学特征分析。通过颗粒、胶质、基质和孔隙度的系统性描述和分析，作者研究了与上述区域相关的石灰岩和大理岩石雕。这种方法能够更好地重建一些石雕的原址，甚至还能回答与石雕原址相关的一些具体问题。本项研究结果可与风格、早期文献研究，一同为今后全世界博物馆所收藏的佛教石灰岩和大理岩石雕提供一个研究框架。

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