

Development of Construction Techniques in the Mamluk Domes of Cairo

by
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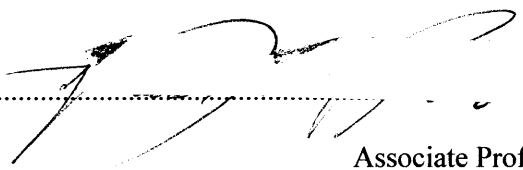
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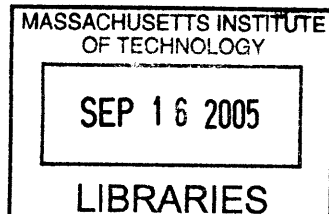
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ABSTRACT

This dissertation reconstructs the building features, the construction methods and the esthetic and structural changes of the Mamluk Mausolea in Cairo (1250-1517 A.D.); a special attention is dedicated to the domes that cover all the Mausolea and that represent an example of high expertise in Mediaeval architecture.

This works document several stages of their construction from the Mausoleum of As-Sawabi, 1285 A.D. to the Funerary Complex of Amir Qurqumas, 1506 A.D. through bibliographic sources, photographic material and restoration reports collected in several libraries and archives where information on the topic is stored. Moreover, three Mausolea belonging to the period of construction in stone: Umm Sultan Sha'ban (1369 A.D.), Farag Ibn Barquq (1389-1411 A.D.) and Amir Khayer Bek (1502 A.D.) are fully documented with survey on site, technical drawing and structural analysis.

Through a detailed analysis of the Mausolea, this work aims to answer to wider questions, such as the role of the patronage in the changes of the architectural features, the differences and the similarities in the construction methods and in the structural behavior between complexes belonging to distinct moment of Mamluk History and the transmission of knowledge in the construction world of Mamluk Cairo.

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*To the Cairene builders
and to my family*

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Preface

This research work, elaborated to fulfill the requirements for the SMarchS degree in the AKPIA program, School of Architecture and Urban Planning at MIT, is the product of a collaboration between the History, Theory and Criticism, and the Building Technology program; a final contribution has been finally provided from the Department of Material Science .

The aim of this thesis is to work jointly to understand Mamluk domes in Medieval Cairo from the point of view of architectonic and urban aesthetic imperatives behind their construction but also to analyze in detail the construction techniques that allowed their realization and the principles embedded in their static equilibrium. In fact, the relation between the adopted construction materials, the overall geometries and the exterior carved ornamentation is of particular importance for these domes.

Aknowledgments

My two mentors at MIT, Professor Nasser Rabbat, and Professor John Ochsendorf, given their strong interest and expertise in the topic of masonry mediaeval architecture, provided me with the tools of analysis that made possible this challenging venture of bridging the two fields of architectural history and structural engineering for a study of Mamluk domed architecture features and structural behavior.

I hereby thank the Aga Khan Program of Islamic Architecture for the financial support during my SmarchS program at MIT and the The Aga Khan team of restoration on the sites in Cairo headed by Christophe Bouleau for their collaboration offered to its maximum extent; they assisted me in the visit on site and they provided graphic, photographic material, information and sample of materials from the restoration fieldwork.

Prof. Heather Lechtman, Prof Linn Hobbs and Elizabeth Hendrix in the department of material science at MIT were a very precious support in the identification of the inner qualities of the building materials.

Prof. D'Amato and Prof. Petruccioli in the Politecnico of Bari with their expertise in masonry structures and in Islamic architecture have supported this work.

Prof. Saleh Lamei Mustafa in Cairo disclosed some precious information deriving from the work of restoration on Mamluk structures.

Wanda Lau, as expert in domes in the department of building technology at MIT have always shared with me her knowledge and experience in the structural behavior of this masonry structures.

SmarchS colleagues and MIT friends Saeed Arida, Scott Francisco, Ajit Singh, Nadya Nilina together with Guido Festuccia in Physics and Isabella Franchini in material science have contributed in the solution of several graphic and architectural problems

Nancy Jones, Administrator in the Department of Architecture was always ready to share with me success and difficulties of this thesis project.

Angela Pisciotta, sometime as a mother, other as a sponsor or companion in the danger and the excitement of the fieldwork never stopped believing in the importance of this project.

A special thanking to the institution and the librarians that have jealously preserved the material on the topic: the Ashmolean Museum in Oxford, the British Library, the Creswell collection at the A.U.C. Rare Books and Special Collections Library, the Egyptian Council of Antiquities, the Harvard Fine Arts Library with Jeff Spurr and the MIT Rotch library with Omar Khaledi and Juanna Wolf.



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Table 1. Map of part of Islamic Cairo from the survey of Egypt in 1951 with the indication of the three Mamluk Mausolea of Umm Sultan Sha'ban and Khayer Bek in the intra muros (bottom left) and Farag Ibn Barquq in the Northern Cemetery,(top right)

Introduction

The architecture of domed Mausolea¹ represents a unique characteristic of the Cairene landscape both for their number and for their variety. There are approximately two hundred domed buildings still standing in old Islamic Cairo, a region roughly 6 km long by 3 km wide (Table 1).² In the crowded urban context the domes are outstanding and become landmarks indicating from far away the presence of a shrine or a mausoleum of a powerful ruler.

This work will focus on unsolved questions of masonry architecture in Medieval Cairo investigating three masonry domed Mamluk³ Mausolea ranging from the XIV to the XVI century A.D. within the perimeter of old Cairo. The choice of the period, which is considered the Renaissance for Islamic Architecture, is given to the exceptional production and experimentation witnessed in the construction of funerary and charitable complexes at the time.⁴ Of particular consideration for this study are the domes topping Mausolea and Mosques which do not only function as a roofing for the structure below but they become a very visible memory of the patrons power and will.

This thesis, using different tools of inquiry, ranging from bibliographic and archival documentation to surveys on the sites in Cairo to a structural analysis of the buildings, inquires whether the driving force behind the invention of challenging building technologies, the use of different materials of construction and the experimentation in the dome decorative patterns is to be attributed to the strong esthetic aim of Sultans and Amirs or to the availability of new techniques among the Cairene builders.

In order to answer this wider question a particular attention has been given to the following issues:

¹ These structures range in date from those constructed in the 10th century with the Fatimid Foundation of Al-Qahira, to those built during the Ayyubide rule (1171-1250) to those of the Mamluks (1250-1517) and the Ottoman conquest (1517-20th century). The complexes are distributed within three zones in Islamic Cairo: the intra muros area, the Southern cemetery (South Qarafa) and the Northern cemetery (North Qarafa).

² The area of Islamic Cairo was named a World Heritage site by UNESCO in 1979. See <http://whc.unesco.org/en/list/>.

³ The Mamluk period is commonly referred to as Medieval Cairo and is divided into two phases corresponding to the two lineages of Mamluks who ruled Cairo: the Bahri Mamluks (1260-1389), originally coming from southern Russia, and the Circassians Mamluks (1389-1517), originally coming from the Caucasus.

- Were Mamluk Mausolea structures built upon the experience and the knowledge of craftsmen and masons or were they the product of their following certain specifications?
- Is it possible to read a linear evolutionary path in the Cairene domed masonry structures?

The very shape of Mamluk domes represents a testing of the boundaries of balance, a game played with intuition, experience, risk, desire and power. It is a bargaining process: how high is too high? What span is too long?

On the one hand, Mamluk domes are defined simply by a number of recurrent elements: round plan, curves described by the tradition of various Islamic arches, and experimental patterns of ornamentation based on repetitive logics. However, those minimal specifications allowed builders to push the boundaries of the static equilibrium

We cannot be sure that these builders could articulate how it worked, there is no availability of written sources or drawings on the construction process of Mamluk complexes; therefore, despite all of the tools of science and measurement acquired over thousands of years, today we can only construct hypothesis on these buildings .

Our method to approach the problem is to observe several cases of Cairene domes and capture differences and similarities in their geometry, material of construction and decoration patterns as illustrated in chapter one. Moreover, the second and third chapter will analyze three Mamluk masonry mausolea focusing on the architecture of their domes with a detailed analysis of their dimensions, static equilibrium and technique of construction and decoration.

Such approach offers the advantages of using the tools of engineers and historians, this can help in distinguishing between reasonable and unreasonable reconstructions, hypotheses and conclusion

Chapter 1. Architecture in Mamluk Cairo

Mamluks and Mamluk Mausolea.

The construction of tombs in the Muslim tradition have always been a controversial issue, the Islamic rule dictates that there should not be a building dedicated to a dead person. The individual should be buried below ground and only a stone with the Coranic script should indicate the presence of a tomb.

However, in Egypt, the cult of the afterlife was anciently rooted and Mamluks, following a tradition already established by the Fatimids and the Ayubids in Cairo topped their funerary structures with wood and masonry domes. However, the Mamluk rulers pushed forward this tradition and the domes placed over mausolea started to be individually designed, utilizing a great variety of patterns.

Mamluks were not originally Muslim, they converted to Islam when they entered in contact with Arabs and this could have been a factor in their choice of developing such magnificent funerary structures despite the strict Islamic rule.

The word Mamluk in Arabic means “owned” and, as Nasser Rabbat (2000) underlines, it can be referred to objects and human beings, in the last case assumes the meaning of slaves.

Mamluk were therefore slaves of Turkoman and Caucasian origin who were bought by Arabs at the beginning of the XIII century for their military qualities, in particular they were amazing horseman who were able to shoot arrows while riding the horses. The chronicles of the time recorded their unprecedented rise to power respect to the Ayubid rule as a natural consequence of the need of that time for security in the Arab world given the threat coming from the Mongul invasions and from the crusades. Finally, the Mamluk were responsible for defeating and the eradication of the crusades from the Holy Land and this factor played a major role in their establishment as a ruling class.

In the Islamic lands they administrated, spanning from the whole Bilad al-Sham (the Middle East to Egypt) they adopted a strict hierarchical system of power at the top of which were the Sultan and then the Amirs. Despite the intrigues and the internal fights that characterize all the period of their rule, they established a rigid control on the economy, the arts of war, the culture and the arts and crafts of the countries that they ruled. They become the promoters of some of the most marvelous complexes that are considered the Renaissance in Islamic Architecture and Cairo witness the maximum splendor of their power.

The most interesting examples of the architecture that they promoted are the funerary complexes dedicated by the Sultans and the Amirs to themselves or to their close relatives; they can be isolated buildings if they are located in the Northern or in the Southern cemetery of Cairo or they can acquire an importance at a urban scale when they are included in the intramuros space of Islamic Cairo .

In the second case, the tomb was often enclosed in a larger complex of religious and charitable buildings such as *madradas* (theological schools), mosques, hospitals, drinking water fountains; the complexes were managed by an endowment documentation named *waqf*⁵.

The high degree of patronage certainly provided an incentive for the wide production of the new architecture complexes and could also have been an important factor in the development of new techniques of construction, in the use of different materials and in the experimentation with innovative geometrical and structural solutions.

No sources have come to us regarding Mamuk Mausolea in the forms of drawings, models or description of the construction works, we can only count on written texts by the historians of the time or on *waqf* documents, which, however do not provide any data on the fabrication process of buildings.

Literature review.

History of Islamic architecture, which is a relatively recent field of investigation if compared to that of Western architecture, use mainly the above sources to reconstruct information on buildings but it faces the absence of main treatises of architecture written by Islamic scholars themselves. There is evidence of several compendia of geometry produced during medieval times, such as those of Tabit Ibn Qurra' (X century) or Al Kashi (XV century), but they seem disconnected from any practical use in the construction field. Their main concern lies, for example, in the definition of different geometries of arches, tracing a sequence of curves with the help of a compass.

An exception is the treatise of the persian Abu al Wafa al-Buzadjani (XIII century) who writes a text named: *Kitab fi ma yahtadju ilayhi al-ummal wa al sunna min al-ashkal al handasiyya* , he writes about what craftsman need to know on the rules of geometric figures⁶.

⁵ Waqf documents are endowments that establish a series of detailed rules on the maintenance of the complexes and on their functioning as charitable institution. They also are instrument that allowed Mamluk patrons to keep the property of the building for their family after their death, avoiding in this way the expropriation by the Government.

⁶ The text is in Farsi and the author of this thesis did not find a translation.

The first scholars who studied Islamic Architecture were Western intellectuals who had been educated in European schools and had been applying the methods of analysis they were familiar with to the new uncatalogued and extensive field that had now become available to them.

One of the founding fathers of the discipline of Islamic Architecture was an English gentleman, K.A.C. Creswell (1879-1974), who provided a fundamental contribution in the field and offered, in the case of the Islamic architecture of Egypt, an extensive production ranging from accurate descriptions of building complexes to architectural drawings to a precious photographic archive⁷.

Creswell approaches Islamic Architecture with an encyclopedic attitude, developing a precise method of analysis supported by a rigorous structure and applying it consistently over a lifetime activity⁸. He is interested in the origin of the form and, consequently, he groups the architectures chronologically to unveil repetition and evolution in every single component of the building. It is a very Darwinian approach and the richness of information that Creswell provides and the systematic arrangement that he makes of them allows him to formulate reconstruction of architectural history that look very structured.

The reason for this thesis to look at Creswell's work, despite the possible misleading factors deriving by the adoption of a specific method⁹, is certainly that he extensively surveyed,

⁷ Creswell's literary production : *The Muslim Architecture of Egypt* (1952), *The Early Muslim Architecture* (1969), in addition to *A Bibliography of the Architecture, Arts and Crafts of Islam* (1984) still represents a milestone in the field.

⁸ A paper titled "Victorian education and K.A.C. Creswell's writing on Islamic Architecture" produced by the author of this thesis for the course "The Historiography of Islamic architecture" held in MIT (Fall 2004) by Prof.Nasser Rabbat offers a deeper analysis of the socio-political circumstances in which Creswell operated and his educational background at the base of his methods.

The XIX century was the period of European military intervention in the Orient and, after 1920, of the establishment of the colonial rules in the provinces previously under the Ottoman sovereignty; such circumstances lead to an increased interest in the East by the West.

Given the general context in which Creswell was working, it is also necessary to note the primitive status of the discipline of Islamic Architecture at the time. While Creswell was well acquainted with the work of a well established and tightly knit academic community of philologically trained Central European scholars that had already established a strong interest in the Islamic world, he strived to establish his own intellectual position and a method of scholarship focused on surveying, cataloguing and describing with an encyclopedic scope. Such approach to the subject was probably influenced by the model of education that Creswell received in his own native country: England, where, the new impulses given by the Industrial revolution and the reforms, also educational ones, that the country instituted during the Victorian period lead to a trustful reliance on scientific models.

⁹ It is important to summarize Creswell's approach because his collection in terms of surveys, descriptions and photographic archives represents the major source of material on the subject. Knowing his methodology will also prevent us from merely following his steps, opening the investigation to other sources of information, observations and conclusions regarding the methods of construction and the structural behavior of Mamluk buildings.

Creswell's approach to Islamic architecture can be summarized as follows:

- Partition of the building structure (separate view of plan, facade, other constituting elements)

photographed and described Cairene complexes; moreover, there is a margin of safety in applying his theories on studying structures that lack of original documentation.

His main book, *The Muslim Architecture of Egypt* in two volumes (the first volume is published in the early 1950's) offers detailed descriptions of Islamic architectures in Cairo since the time of its foundation with the Fatimids (10th century) up to Bahri Mamluk (14th century). Unfortunately, because of the sudden end of Creswell's life, his surveys and descriptions cease with the period of the first half of the 14th century. Each structure is analyzed in its totality, including minor components and in the first volume Creswell adopts comparative tables to classify the domed Mausolea of the cemetery of Aswan .¹⁰

This dissertation takes in great consideration Creswell as a source of data on the Cairene structures, however it is also interested in other tools of investigation to understand Mamluk Mausolea and the shapes of their domes.

The study of precedents in domed structures dates back to two major empires: the Byzantine (312-1453 A.D.), as an inheritor of the classical tradition, and the pre-Islamic Zoroastrian Sasanid empire (226-642 A.D.) The Byzantine adopted the dome, mainly hemispherical, for sacred structures developing in the Syrian regions the use of stone for this kind of structure, while the Sasanids produced amazingly high funerary buildings known as Tomb Towers which belonged to the tradition of brick construction. K.A.C. Creswell recognizes the importance of Persia in the development of the dome type (Burlington Magazine, 1913).

The experimentation in dome shapes that took place in Persia is unprecedented and several new techniques were developed to allow the passage from wood dome structures to those of brick, and from conic and hemispherical shapes to bulbous shapes and to domes with multiple centers (Table 1 Fig.b,d).

-
- Description and comparisons of buildings constructed in different times and in different parts of the Islamic world. Such analysis is conducted through the addition and subtraction of their parts.
 - Grouping of architectural elements in tables (construction of series)
 - Statistic deductions regarding the percentage of occurrence of an architectural type or element.
 - Research of the original plan of the building (an interest in chronology that comes also from the contemporary publications on the nascent discipline of Archaeology).

Creswell lists all the buildings under analysis in chronological order because he is constantly in search for an evolutionary path in their typology; his interest involves each single element that constitutes the architecture, including their materials of construction.

¹⁰ In this case he produces a tabulated classification of Mausolea supporting with this tool one of his theses already present in another article in the Burlington magazine in 1914 titled "Persian Domes Before 1400" where he identifies the zone of transition between the dome itself and the vertical walls as a crucial element both for the widespread use of domes to cover rooms and for the possible evolution of the dome element itself.

The use of domes in Persia dates back to the 3rd millennium B.C.; the first dome still standing was built in Firuzabad, South West Iran, about 1800 years ago, ovoid domes and parabolic ones were erected up to the VII century A.D. Low saucer-like domes were constructed later. Double shell domes appeared in the XI century A.D. In the XII century A.D., conical domes, rising to a sharp peak, crowned circular or octagonal structures while high domes were placed on tall drums in the fourteenth century. Bulbous domes became current later and were followed in the XVIII century by onion-shaped domes.

The changes in the shape of the dome probably followed necessities, cultural beliefs or the will of their patrons, however, the evolution in construction techniques and solutions to structural problems allowed such changes .

In Cairo, the challenge of constructing domes with larger spans and heights started with the use of wood; in the old Fustat before the foundation of Cairo by the Fatimid (969 A.D), the first example of a monumental dome was realized on the mosque of Ahmad Ibn Tulun (870-879 A.D), constructed in wood, with a span of 15.5 meters.

Another example of a wooden dome is the one that crowns the tomb chamber of the complex of Sultan Hasan (1356-1360), in the middle Mamluk period. Sultan Hasan's complex was a colossal project and his square tomb chamber is the largest domed Mausoleum of Cairo; it was 20 meters wide by 30 meters tall. According to Cairene builders of that period probably did not have the expertise to reach such a span with a masonry structure and they still relied on wood, (Blair and Bloom 1995).

The majority of Mamluk domes however, up to the first half of the 14th century when the shift to stone occurs, are constructed in brick.

In 1976, Christel Kessler, a colleague of Creswell, following his method of looking for an evolutionary path in the Islamic buildings, publishes *The Carved Masonry Domes of Mediaeval Cairo*, identifying an improvement in the relation between structure and decoration in the passage from exposed brick to plastered brick to stone carved domes. Moreover, she underlines an evolution in the treatment of the joints that allows the decoration patterns of several generations of carved stone domes to become not only more complicated but also increasingly congruent with the underlying grid of stone ashlar, (Table 3).

In the following chapters, this passage will be analyzed and, with the help of the structural analysis we will try to demonstrate how, some problems of equilibrium were common both in the brick and in the stone domes and it will show some of the answers that Cairene masons were giving to those problems.

The average dimensions of domes constructed in brick usually range between 4 and 7 meters of diameter and between 4 and 7.5 meters of height. After 1322 A.C, when the shift in materials occurs, the overall dimensions for stone domes do not vary significantly; however, they become more consistent, ranging often between 8 to 10 meters of diameter and between 7 to 11 meters of height. Exceptions to the general rule occur as in the case of one of the three stone domes analyzed in chapter two, the Mausolum of Farag Ibn Barquq which records a diameter of 16meters and a height of 12.8 meters. An important change, however, has to be pointed out in regard to the thickness of the dome section; while the majority of the structures in brick range from 40 to 50 cm, the ones in stone range from 32 to 43 cm only.

This chapter includes the images of 26 domes spanning from 1250 to 1517 A.D., the plates, arranged in chronological order, will be used in this and in the following sections to look at innovations and revivals in geometries, materials, construction techniques and decorative solutions in Mamluk times.

Concerning the decoration, the Egyptian first stone domes were mainly ribbed on the outside, reflecting the tradition of the brick domes and they were in some case plastered on the outside. The increased accuracy in the cutting of the stone and in the treatment of the joints between the stone ashlar ended the practice of covering the domes with plaster, as had been the case for the ribbed brick domes (Fig.1.1,1.2) and the first stone ones (Fig. 1.7).

In the 1370s A.D., the spiral ribbed decoration was developed as in the Amir Iljay Al Yusufi Funerary complex (Fig. 1.9), at the end of the 14th century zig zag decoration becomes a common pattern (Fig. 1.13, 1.14, 1.15), followed by interlaced star pattern and floral motives in the second half of the 15th century and first decade of the 16th (Fig. 1.20,1.21); a return to the zig zag pattern is witnessed at the end of the 15th century and beginning of the 16th.

Christel Kessler tackles the passage from brick to stone in Cairene domes, she believes that an important change occurs when the ribs do not have anymore a structural function as in the brick domes, but they became only a decorative addition for the stone ones (Table 3). This is particularly evident in the spiral ribbed decoration and this thesis offers evidence taken in the field and through research in photographic archival that at least in the upper courses of the stone domes the decoration are stone tiles of a thickness of 15-20 cm applied to the bearing structure (see paragraph in chapter 3 on *Dimensions and geometries and Decoration*).

The following chapters will contain accurate descriptive and structural analysis of three Mamluk mausolea topped with stone carved domes (Table 3), Umm Sultan Sha'ban (1369 A.D.) (Fig. 1.8), Farag Ibn Barquq (1389-1411A.D), (Fig. 1.13) and Amir Khayer Bek (1502 A.D.), (Fig. 1.25) of which we are including here a general description (Table 4).

Three domed masonry funerary complexes:

Mausoleum of Umm al-Sultan Sha'ban (Fig. 1.8)

The first example of a stone dome belonging to the Mamluk tradition that this study considers is one of the two domes (the south Eastern one, the bigger one) topping the mausoleum of Umm Sultan Sha'ban in the Intra Muros Islamic Cairo built in 1369A.C.

The dome is constructed using stone ashlar decreasing in size from the end of the drum to the top of the dome, which produces a perspective ribbed decoration pattern. The decorated portion of the dome measures 4.85 meters plus the 2.60 meters of drum, the dome is supported by a vertical wall of 16 meters with a thickness ranging from 1.10m to 1.67m. On four side of the wall right below the drum there are step- like buttresses. The diameter of the dome at the drum is of 5.30 meters.

According to the classification of Kessler in *The Carved Masonry Domes of Medieval Cairo* (Table 3), this dome belongs to the period that she calls "Stage II: structure in conflict with decoration" and the level of soundness of the structure is manifested by the cracks that can be observed in the masonry of the dome (Fig.2.3a,b,c,d) . However it is fair to say that the cracks were not present in the pictures that Creswell took in the first half of the 20th century and they appeared after the earthquake of 1992 (Fig.)

Mausoleum of Farag Ibn Barquq (Fig.1.13)

The second stone dome object of this thesis is the north east dome of the Mausoleum of Farag Ibn Barquq in the North Cemetery of Cairo (1398-1411).

The decorated portion is composed of 54 rings carved with a zig zag pattern), reaches an height of 12 meters, plus a drum of 3 meters. The ashlar constituting the dome have an annular arrangement as in the dome of Umm al-Sultan Sha'ban but they are cut and assembled more precisely. According to Kessler classification this domes of Farag Ibn Barquq belongs to "Stage III, Decoration and structure first properly coordinated".

To support the 15 meters dome there is a wall of 18 meters of diameter for 2 meters of thickness. On four side of the wall right below the drum there are step- like buttresses as in the Mausoleum of Umm Sultan Sha'ban but they are shaped as round moldings. The diameter of the dome at its springing from the drum is of 14.28meters.

Mausoleum of Khayer Bek (Fig. 1.25)

The third stone dome under analysis is the one covering the mausoleum of Khayer Bek in the Intra muros Islamic Cairo (1502A.C.)

It is ogival in form and it was erected on the principle of utilizing carefully dressed stone wedges; the number of rings constituting the decorated portion of the dome is 26, this portion reach an height of 7.32 meters plus an inferior drum of 3 meters.

The overall dimension of the dome is therefore 10 meters, this is standing on a vertical wall of 16 meters of height and a thickness ranging from 1.10 to 2.30 meters that the structural analysis have proved having an important role in the equilibrium of the structure.

The above general data on the three complexes, together with the original images from the restoration works will provide the reader with an exhaustive documentation on the three structures which represents different stages in the construction and decoration of Mamluk domes. The aim is to have a better understanding of the structural and stylistic changes of the domes in the timeframe to which this complexes belong.

Chapter 2: Methodology

Archival research

A considerable portion of this study has developed in archives and libraries that have in custody the work of K.A.C. Creswell such as the Ashmolean Museum in Oxford, the Creswell collection at the A.U.C. Rare Books and Special Collections Library and the Harvard Fine Arts Library. In the Ashmolean are preserved the original slides taken by K.A.C. Creswell and the unpublished description of four complexes belonging to the last period of the Bahri Mamluks.

In other institutions such the British Library and the MIT Rotch library, the author found rare bibliography on the subject in form of texts and articles. In the headquarters of the Egyptian Council of Antiquities in the Citadel of Cairo, an unbelievable quantity of images was available on Islamic complexes in Cairo contained in archival boxes; a single box usually contains material on one or two buildings. Technical drawings on the complexes, produced in different periods, starting at the beginning of the XX century are also present.

The material collected in all these institutions have been extremely precious to make observations and establishing comparisons on Mamluk complexes.

Restoration reports and survey on the site

Umm al- Sultan Sha'ban (Fig. 2.1-2.2)

The restoration works currently carried out on the dome by the Aga Khan Trust for Culture have provided important evidence not only on the layout of the cracks but also on some of the features of the dome's upper part, features that will appear as common structural solutions for the Mamluk buildings.

Some of these findings are:

- the presence of a wood post hidden below the hollow metal spire holding the crescent moon characteristic of all mausolea and mosques (Fig. 2.4a,b,c-2.5b,c);
- the double profile of the inner and outer dome on the top: the difference between the two profiles is filled with rubble to keep the wood post stable (Fig.2.5a,2.7b);
- the fact that the stone ashlar constituting the annular rings visible from inside and outside are the same piece (Fig.2.6b);
- the absence of horizontal connections between the ashlar (Fig.2.6b) constituting the annular rings witnessed in later stone domes such as the one of the Mausoleum of Farag Ibn Barquq (1398 A.D.) and the Madrasa of Al-Gawhariya (1430-40 A.D.);

- the marginal structural role of the mortar between the joints (Fig. 2.6c)

Concerning the cracks, they run along the line of the joints between the stone ashlars, reproducing step-like cracks (Fig.2.a,c,d) , these kind of fractures, (although mainly emerged after the earthquake of 1992) reflect the lack of soundness in the structural connection of the joints.

Farag Ibn Barquq (Fig. 2.10)

The report of the restoration work executed in the late 1960s on the dome attests the presence of connection features shaped as dovetail¹¹ (Fig.3.5a) between the ashlars assembled to shape the rings. These connections are in teak wood and they are embedded in the stone of the voussoirs ; the report does not mention if they are present only in one region of the dome.

The structural analysis of the dome presented in this work is based on the accurate drawings mentioned above and on an additional survey carried out in April 2005 in the field by the author of this thesis using a LaserDisto to confirm the internal profile of the dome (Fig.2.16)

Khayer Bek mausoleum (Fig. 2.19)

The Aga Khan Trust for Culture is currently (2005) in charge of the restoration of Khayer Bek complex and has produced several detailed CAD drawings using a Total Station to survey the interior of the complex utilizing photogrammetric techniques to reproduce the geometry of the exterior, including the decorated dome (Fig.2.20).

The current restoration works are dismantling the upper part to almost one meter (Fig.2.30) and replacing the damaged blocks.

This ongoing restoration process has already revealed some important features of the dome that influence both its structural behavior and its aesthetic appearance; the restoration will provide us with more information as it proceeds. For instance, it is now clear that the Khayer Bek dome shares common structural features with other domes of the same Mamluk tradition which have been previously restored and analyzed. One of these features is the presence of stone tiles constituting the last rings of the conical top profile of the dome (Fig.2.29a,b) A number of these are carved, while the very last ones are smooth; they serve to reach a desired shape, hold the spire, and distribute the weight to the inner profile of the dome. They therefore constitute the top part of a discontinuous double dome and the space between the inner and the outer profile is filled

¹¹ See Salah Lamei Mustafa in *Kloster Und Mausoleum des Farag Ibn Barquq in Kairo*, 1968 pg .25 n.92.

with earth and rubble.¹² The inner geometrical form of this dome differentiates from its outer form, as indicated by the section and by the three dimensional reconstruction (Fig.2.24,2.26).

A second clue derived from the restoration works concerns the entire section of the dome: at the springing of the drum the thickness of the section measures 43 cm and it is constant until the top part of the dome where it doubles in dimension. It is exactly at that point that the profile of the dome divides into an internal and external component. After a first analysis on site, the stone ashlar constituting the rings seem to be the same ones from inside and outside, but after the repairing process it will be obvious whether or not there are several layers as it is true for the upper part. A third contribution will be the final understanding of the geometry of the top inner ring of the Khayer Bek dome and its role as key stone in the inner profile (Fig.2.2).

Measurements done by the author on the fieldwork show evidence of flatness of the top inner ring; once dismantled, the nature of the material and its exact profile will become clearer.

The surveys, conducted by the author in the month of April 2005 also highlighted the pattern of the cracks (Fig), which are minor and different in behavior from the ones of Umm Sultan Sha'ban (Fig.2.6). This is clear proof of an improvement in techniques of cutting stone ashlars and in the way they were assembled. It may also be proof of the presence of an additional system of horizontal and vertical connections between the ashlars.¹³ This will be finally verified after the completion of the restoration work.

Additional information acquired during the restoration work on Khayer Bek reveals the presence of small wood pegs emerging from the external and internal annular rings (Fig.2.7,2.8), most often occurring between the joints but in some cases coming out also from the external decoration. These are important traces that we interpret mainly as tools employed during the construction process to level the heavy stone ashlars when they were put in place one by one to constitute each ring and which were probably placed in the mortar.

However, the position of the above mentioned pegs is not the same on the inside and the outside. The difference in their pattern suggests that they were used sometimes from the interior side and sometimes from the exterior side to level the stones during construction. In some cases they may have been correlated with the decoration, representing guidelines for the masons carving the stone (Fig.2.27). They seem to act as local setting blocks for the stone and do not

¹²A previous structural analysis has been carried out for the same dome considering the top part as full masonry. Figure presents both the cases of a structural analysis for a full masonry dome top and an hollow one.

¹³ Indications of several additional methods to ensure horizontal and vertical connection between the stone ashlars have been attested by several restoration reports. Examples are the mausoleum of Qurqumas and Farag Ibn Barquq and the Madrasa Al- Gawhariya.

extend all the way through the section of the dome, this is verified by their different position in the inside and outside of the dome.

Structural Analysis

Structural insights and calculations can definitely support inquiries of interest for historians and structural engineers such as Jacques Heyman¹⁴ and Santiago Huerta¹⁵ have produced an extensive literature on the subject of domes behavior of equilibrium.

The analysis of the behavior of a masonry architecture can possibly explain several more hidden properties of a structure and can help to identify:

- The sequence of its construction (Fig.3.4a,b,c)
- The reasons for its entire or partial collapse. (Fig.3.1,3.2,3.3)
- The original semblance of structures that have been lost or of which only partial records remain.
- The intentions and tools of past designers, including geometric theories and their relation with the work of architects and masons.

Moreover, a structural analysis that draws on historian's literary and graphic principal sources can provide further knowledge and insights into the architectural character and detailing and can help defining which conclusions are more reasonable.

The critical problem for the builders of the dome is the prediction and control of the curve along which the load is transmitted to the drum and subsequently to the vertical walls.

In this work, two are the main tools of inquiry applied to the three masonry domes: the three dimensional reconstruction of the stereotomy of the dome taken as a whole and then divided in its components (Fig.2.17, 2.26) and a structural analysis performed with the method of the funicular polygon (Fig.2.7,2.8).¹⁶ This model takes into consideration the non-homogeneities of the cross sections and changing characteristic of the material, it differs from the finite elements models since it does not provide a unique answer for the condition of equilibrium of a structure, but allows the user to explore different possible conditions. The graphic method is therefore closer to the true behavior of the structure and it establishes the limits between which

¹⁴ Jacques Heyman is Professor of structural engineering in the University of Cambridge, England.

¹⁵ Santiago Huerta is Professor of structural engineering in the Escuela Técnica Superior de Arquitectura de Madrid

¹⁶ The funicular polygon is graphic method tackling the equilibrium of the dome structure in its whole and ring by ring simulating the construction process

this behavior must always lie, providing a range of possibilities within the limits. This procedure unveils the principal internal actions of compression or tension and strongly correlates the overall section and its components with their weights. The direct indication of load paths or thrust lines provides a close result to what we intuitively sense it can be the behavior of the structure, and this can help in developing intuitive understanding for preservationists. Specifically, we consider the combined effects of geometry, the height of the dome, weight and the path of internal forces.

Such method of structural analysis can be applied to a building in its whole as well as to an isolated architectural component; however, the basic principle behind it is the analysis of the overall equilibrium which can explain why the building is still standing or the reasons for its collapse. Moreover Heyman theorizes that it is possible to analyze the equilibrium of one slice of the dome at the time, based on the assumption that when the construction of a dome is completed, the occurring cracks will follow a meridional path, therefore in order for the dome not to collapse an equilibrium of each slice is implied.

The three stone Cairene domes, will be analyzed through the same method.

Several precise steps have been taken in order to perform such analysis:

- The construction of a three dimensional model of each one of the dome
- The isolation of a slice of 20 degree of the dome for the analysis of its equilibrium (Fig.2.8,2.15,2.25) ¹⁷
- The subdivision of the internal section of the dome in a number of stone voisseoirs corresponding to the real model (Fig.2.8,2.15,2.25) . Each portion is characterized by a volume and a weight.
- The identification of the centroid for each one of those volumes and the application of the weight in units of Newton to each one.

The weights of all the ashlar, drawn to scale of 1N= 1mm and summed up starting from the one of the top piece will be used to draw the funicular polygon (Fig.2.) Finally the funicular polygon will be closed by connecting each end of the segment representing the weights to a hypothesized pole. The magnitudes of these forces are easy to read in the diagram of the funicular polygon (Fig.2.8,2.15,2.25). The result will be several segments that transferred within the dome section will provide one of the possible infinite paths of the load line. This study have considered the load line at the limit of its fitting within the dome section (Fig.2.7,2.14,2.24).

Chapter 3: Observations and findings on Cairene Mamluk Mausolea

Materials and methods of construction

The understanding of the general behavior of masonry structures is a necessary condition to read architecture that is constructed in this material. Unlike timber, masonry's main strength is expressed under compression stresses, while its main weakness lies in the bending capacity. Therefore, the equilibrium of the masonry structures largely relies on internal compressions and the transmissions of their self weights and additional loads to the ground.

Self weight is usually the predominant force burdening the structure and its values are generally much smaller than the resistance of the masonry. Therefore, even if cracks occur, they generally influence the path that the weight follows within the structure that is assuming a deformed condition, but rarely they threaten its stability.

The critical moment in the equilibrium of a masonry building is the construction phase when the equilibrium can be affected by the sequence of construction or by the effectiveness of temporary support such as centering or mortar. The author of this thesis, based on the knowledge of Masonry structures acquired through literature on the subject, classes at MIT¹⁸, restoration data and archival images (Fig.3.2,3.3) has reconstructed some of the possible methods used in the process of construction for this domes (Fig.3.4a,b,c)

Collapse will be more likely during or right after the construction, while a later failure will be probably due to excessive deformations and drastic changes of the load path; the cracks or local compressive failures represent additional threatening components in this case.

The role of the mortar in the overall stability is ambiguous; it gains in strength and stiffness along the centuries but this phenomenon does not have a major role in the overall stability of the structure, while mortar can have an relevant function during the construction process¹⁹.

Once the structure is completed, the compression load path is established among the stone ashlar and the equilibrium depends on their stereotomy (see reconstruction drawing for the domes Fig. 3.) . After completion, the structure will continue experiencing minor variations such as shrinkage or creep of the mortar or alternate opening and closing of fissures²⁰, which can occur due to the changes in temperature and humidity.

¹⁸ Prof. John Ochsendorf offered two courses in the department of building technology at MIT on the behavior of masonry structures in the Fall 2003 and Spring 2004.

¹⁹ A sample of the mortar from the Mausoleum of Amir Khayer Bek is currently under study in the department of material science. The analysis will be undertaken with a Scanning Electron Microscope that will provide information on the property of the mortar.

²⁰ See restoration report of The Royal Danish Academy of Fine Arts. (1996). *Al- Madrasa al -Gawhariya, A Restoration Project in Cairo*. Copenhagen : School of Architecture Publishers.

As Rowland Mainstone underlines (1999), another fundamental component in the behavior of a masonry structure is the lack of homogeneity for elements like the cross section of the piers or their reciprocal tightness.

This brings important considerations, including the following:

- The load compression force and its distribution between different supports can take infinite possible paths within the masonry structure (However, by the time the opening and growth of cracks and distance between the joints and the deterioration of materials will narrow down the range of possibilities).
- The presence of the vertical joints introduces weaknesses on the overall strength and stiffness in the structure.

Given all the above considerations, the structural analysis applied to the three Mamluk domes has given the following results:

- The line of thrust do not fit completely in the section of the dome
- Meridional stress is not sufficient to ensure the stability of the dome
- Hoop stresses are definitely needed and that is established after the construction of the dome and probably already by the completion of each ring.
- The best-fitting load path in the section of the three domes is very similar despite the differences in their dimensions.
- The vertical walls and 4 step like buttresses at the bottom corners of the drum contribute, given their thickness and their position, to the equilibrium of the structure.

Dimensions and geometries

After circa 1322 A.D. , the stone ribbed and carved domes began to prevail; out of a known number of 76 domes only 16 are in brick. This data, acquired from a catalogue²¹ constructed by the author of this thesis on a sample of 113 Cairene domes that were recorded in the first half of the XIX century by the Egyptian Council of Antiquities, show that there was a strong preference for the stone material but this did not lead to the total disappearance of the brick.

²¹ The Catalogue was the final paper for the course “ The Architecture of Cairo” held by Prof Nasser Rabbat at MIT in the Spring semester 2005.

The same catalogue gives also a clear indication of the change in the dimension and geometry of the domes. Data have been collected through several bibliographic sources; however, the majority have been found in Creswell's *Muslim Architecture of Egypt*. The maximum diameter recorded for brick domes before 1322 A.C is 12 meters for a height of 8 meters (Sultan Qala'un funerary complex), followed by Sultan Baybars Al-Jashankir complex (diameter 11 m, height 6.7m), Ashraf Khalil Mausoleum (diameter 10.5 m, height of 6.65m) , and the fallen dome of Fatimah Khatun Mausoleum of which is known only the diameter of 10 meters.

The soundness of a dome structure is based on several components within which:

- the properties of the material in use: wood (it allows tension stresses), masonry (brick and stone, they work in compression).
- the congruence of shape between the end of the drum and the spring of the dome (ex. Circular dome set on a circular base)
- the development of a zone of transition when the base of the dome is no longer circular but acquires a polygonal shape (square, octagon, etc.)

Experiments in the construction methods allowed domes to reach higher height as well as articulated transitional zones between the dome and the vertical walls.

In the construction of a dome, bricks can be assembled according to three methods (Table 2)

- a) Corbelled. Bricks are placed in horizontal courses and the upper row protrudes over the lower row of bricks toward the center.
- b) The direction of bricks is always normal to the generating curve of the dome surface.
- c) Few ribs are first erected, after which bricks are inserted between them to complete the dome.

Some general observed characteristic in the geometries of Mamluk domes are the followings:

- The Cairene stone domes are generally single shell domes with few exceptions such as Al Sultaniyya (1350-60A.C.) (Fig).
- They follow the second method of construction where the direction of the stone ashlar is normal to the generating curve of the dome surface. The ashlars are assembled to constitute circular rings and the final dome is constituted by the overlapping of such rings.
- The internal and external dome profiles are drawn on two centers (Fig.3.) and not only one, as in the case of the hemispherical dome, therefore constituting a shape of pointed dome. Such features will be common for the following stone domes as well as for the division of the dome profile into three main sections: the elongated drum, the curved portion that is drawn on one of the centers and the top part that follow almost a straight line and terminates the pointed profile.

- The section of the three domes have in common a division in three portions: the drum, a curve part that is drawn upon one of the two center constituting the pointed dome and a top linear part. The structural equilibrium appears to be dependent on such partition.
- The drum is surmounted by the first decorated part of the dome of which the first rings are vertical as well as the drum.

All the observations above can contribute reconstructing common principles and exceptions in the Mamluk structures; however, in the lack of sources on the tools and methodology during construction processes, our main instrument of inquiry remains the building itself.

There are several questions that architectural historians as well as specialists in built heritage preservation need to answer when analyzing a historic structure and to which the answers could not be sufficiently provided within esthetic or historic criteria.

The issues that concern art historians range from the necessity to date a building, to the possibility of establishing influences or exchanges in style, techniques of constructions and use of different materials. The problem that concerns preservationists, on the other hand, can be related to the question of the potential structural collapse, the necessity for a restoration process, or the authenticity in the reconstruction of a missing or damaged element.

As an example of a problematic that concern art historians, K.A.C. Creswell developed a theory on of evolution for pointed arches²², asserting that the farther apart the two centers that define the pointed arch, the later the construction of the arch itself.

The author of this thesis has been testing Creswell's theory on several Mamluk pointed domes and the results are that there is effectively an increasing distance between the two centers from older to later domes; however, the rule is not always going in one direction since there are later domes with a less pointed profile than previous ones. In the three cases analyzed of Mamluk stone domes, his theory is applicable since the distance between the two centers spans from 1.14 meters in a the dome of 1369 A.C to 1.81m in the dome of 1398-1411 a.c. to 2.03m in the dome of 1502A.C.(Fig. 2.7,2.13,2.24)

A second example of a problematic raised by art historians is the reason for the passage from brick to stone in dome construction in Cairo. According to Kessler, a possible reason is the need for a greater stability, or simply a line of tradition coming from outside the country.

Creswell, instead, assumes that the appearance in a given context of a particular architectonic element has to be attributed to the status of construction techniques available *in loco* or eventually

²² Warren, J. (1991) *Creswell's use of the theory of dating by the acuteness of the pointed arches in early Muslim architecture*, Muqarnas,(8)59-65.

borrowed from a place where there is a precedent, rather than to a precise esthetic choice of the individuals involved in its construction.²³

The present work supports the hypothesis that, given the visible repetition in the method of assembling the stone ashlars and the coincidence between the structural grid and the decorative pattern of the domes, the Mamluk system of construction in stone would be as replicable as the brick system but it would offer several advantages.

These advantages include increased durability, a more precise construction condition even on allowing a thinner section the possibility of reaching larger spans and heights, moreover the new material gives the opportunity of carving the stone, and therefore obtaining an infinite possibility of decoration based on the underlying grid. The limestone used for the construction (Appendix ppg. 105-108) is known for its characteristic of softness once extracted from the caves, working on this kind of stones would be like working on wood without the problems the latter presents of following the fibers direction while carving.

On the other hand, the construction in stone presents some disadvantages like the necessity to lift heavy ashlars in place to shape the overlapping rings constituting the dome and to keep each block in place before the completion of each ring. Probably the last task was achieved with methods such as minor centering together with the use of gypsum that is a fast dry mortar (Fig.3.4a,c, Appendix p.109). Christel Kessler inquires into the changes in cutting, assemblage and carving of stone ashlars to unveil a possible pattern of development in the Cairene domes (Table 3).

Decoration

The decoration pattern of Mamluk domes works in a tiling pattern, which is repeated until it forms a sphere. This repetition is based on multiples of 4 (4, 8, 16, 32) in all Cairene brick ribbed domes and decorated carved stone domes. In the case of Umm Sultan Sha'ban there are 32 slices of decoration repeated and 32 are the stone ashlars assembled to constitute the ring (Fig.2.9); in Farag Ibn Barquq there are 28 slices and 56 stone ashlars (2.18); in Khayer Beck the design of one slice is repeated 16 times to complete the sphere and the stone ashlars per ring are 32 except in the upper conical part when they become only 16 (Fig.3.6).

This suggests the possibility that they were carved based on a drawing representing at least one of the slices to be repeated. The main dispute still remaining is whether the carving on the stones

²³ Hillenbrand's opinion instead is that Persian masons could have brought to Egypt the idea of the ribbed dome, an idea not intrinsically far-fetched since several earlier Cairene monuments bear unmistakable traces of Saljuq influence.

was done before the dome was assembled, as the coincidence between the ashlar and its decoration suggests, along with the rhythm A-B-A-B meaning that the complex carving pattern is created by the use of two different carved ashlar per ring (Figure 3.6) that the decorated ashlar follow, or whether most of the work was done before assemblage and the finishing was executed afterward, as several differences in the carving of the details may also attest. As the rings of the dome extend toward the crown, the new ring is added on top in such a way as to match the pattern of the previous ring. In all cases, the carving of the patterns for each ring is straightforward since each stone in the ring corresponds to its neighbors on either side and below. In this way, a complex carving pattern emerges, which grows from the base of the dome toward the crown, yet is composed of relatively simply individual elements. We can only hazard hypotheses based on observations but it is possible that this carving pattern was not premeditated but that it emerged during the construction of the dome in together with the addition of each ring linking in this way the construction and the decoration of the dome; the design on the dome follows a double curvature.

However, if the builders produced a design on paper²⁴ or other support for at least one portion of the dome decoration to be repeated, then the drawing was probably bi-dimensionally approximated to a single curvature. This would have allowed the carvers to have an idea of which carving pattern needed to be placed on each ashlar.²⁵ It seems clear that the number of stones was used to help dictate the geometry of the carved patterns, which are made up of repeated motifs reproduced on each stone.

²⁴ There are no surviving drawings or written sources describing the process of construction and decoration of the Cairene domes.

²⁵ This hypothesis can be applied whether the dome was carved before or after construction.

Conclusions

The three cases of Mamluk domes analyzed in their overall geometry and by their single components (carved stone voussoirs) allow us to understand what was the basic knowledge of construction in Mamluk times and which changes occurred to satisfy the aim of stronger, higher and more complex decorated domes.

There is a major change in the cutting, assemblage and connection of the stone ashlar from Umm Sultan Sha'ban to Farag Ibn Barquq and the soundness of the new method is visible in the different dimensions of the crackings between the two domes.

Farag Ibn Barquq represents also a further step in the decoration pattern since it overcomes the ribbed aspect of the previous dome and introduces the zig zag one. On the other hand the decoration of Farag Ibn Barquq dome appears as very much simpler respect to the one of Khayer Bek even if the layout of the grid on which both designs are based is essentially the same one.

In terms of structural behavior, from the first to the last, the structures become more daring because the drum elongates, the shape of the dome becomes more pointed and this not only for the increased distance between the two centers that define the pointed profile, but also because the top conical part of the dome increases itself in height. However, the ratio between the diameter and the thickness of the section has its smaller value in the middle dome (Farag Ibn Barquq with $14.28\text{m}/0.35\text{m}=0.0245$) that becomes also very hazardous if compared to the previous Umm Sultan Sha'ban ($5.30\text{m}/0.33\text{m}=0.062$) and the following Khayer Bek ($7.46\text{m}/0.43\text{m}=0.057$).

Furthermore, it seems there was a general understanding since the beginning of the stone domes tradition of the transmission of the compression forces since the diagram resulting from the structural analysis indicates a very similar path for the internal load in all the three domes²⁶.

The understanding of the internal forces allowed also the builders to take precautions for the region where the load stress could have exited the section because of an excessive hoop stress for example, and avoid this possibility with several methods. These included the accurate cutting of the stones to be assembled in rings, and the different inventive connections (horizontal and vertical) between the ashlar, generating hoop forces that contribute to the equilibrium.²⁷

²⁶ the load path for the three domes is indicated in the section drawings

²⁷ Inventive connections range from the dovetail cut in the stone ashlar that accommodate a wood horizontal connection of the same shape in the Mausoleum of Farag Ibn Barquq, to the iron cramps sunk into the top surface of the stone ashlar in the dome of Al-Madrassa Al-Gawhariya (Cairo, 1430-1440 A.D.) and in the mausoleum of Qurqumas (1506) to a carved - concave shaped channel to be filled with mortar in the top and bottom part of each ashlar found in a fallen dome next to the complex of Barsbay in the Northern cemetery (mid XV century).

What makes these Mamluk domes interesting is that they are apparently "illogical" and that on a first glance they appear as they shouldn't work. Their structure derives from a 'system' of 'information' transferred from one mason to another one. It is a path of culturally embedded knowledge that was deeply rooted in 'doing', not in documenting and reproducing based on those documents. This often led to much more 'complex' outcomes because builders and architects were not tied to representational systems. But on the other hand it can also mean that they were vastly limited in their ability to exponentially build on the previous knowledge of others. In these domes (there are at least one hundred of them still standing dating back to Mamluk times) we have proved that there was a progressive understanding of how the structure could become more sound and how the decoration could increase its level of intricacy; however as the study of a larger number of them has shown the process was not always monodirectional and a later dome could present again a decoration and a structure behavior less daring than a previous one.

Tradition as a way of transferring knowledge tends to only allow for slow innovation and it is probably more difficult to communicate after a drastic change of a strong central power.

This is probably one of the causes why after the occupation of Egypt by the Ottomans the Mamluk tradition of dome construction was lost and the fact that no models, drawings or written descriptions has ever been found for this architecture is an additional proof of the way the knowledge was transmitted.

The construction of Mamluk domes were probably the product of several factors within which the patron will of keeping his tomb protected by a solid and beautiful roofing, the fact that the tomb could be possibly visible from far away and this was achieved with the height reached by the dome. Moreover, the uniqueness of the decoration pattern guaranteed, and as a matter of fact this happen until today in Cairo, to associate each Mausolea, and when it is the case, the complex annexed to it with the name of the Sultan or the Amir who is buried in there.

The shape and the decoration of the dome served all these proposes and the fact that the non-structural conical top part progressively elongates from the time of the Mausoleum of Umm al-Sultan Sha'ban to the one of the Amir Khayer Bek Mausoleum is an additional proof that there was an esthetic aim behind the construction features of these complexes.

The present work has provided further knowledge on Mamluk domes through several tools of investigation (structural analysis, surveys, bibliographic documentation) and still has not disproved the conclusion just mentioned above. The three domes share several features as for their stereotomy and decoration methods and this indicate that their structural behavior and esthetic principles was of public domain.

However, they still offer different solutions to similar problems suggesting the independence and inventiveness of their constructors. Moreover another striking aspect is the possibility to have repeated the same design even after a more complicated one has already been developed. I am thinking in this case to the re-proposition of the zig zag pattern even after the development of the more complicated floral and star pattern one,

It happens in Mamluk Cairo where the border between evolution and tradition develops an unique and unrepeatable configuration.

Chapter 1 (Images)
Mamluks and Mamluk Mausolea

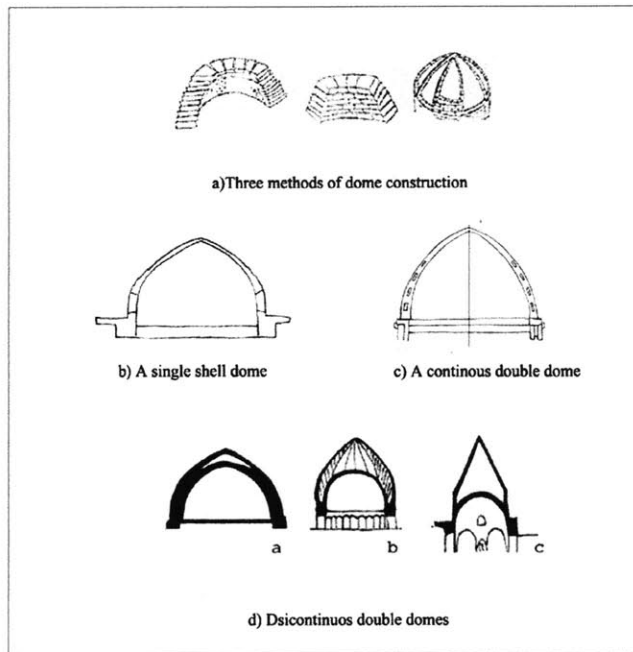


Table 2 Examples of dome sections for single and double domes in the Islamic tradition. Source: Images after M.M. Hejazi, Historical buildings of Iran: their architecture and structure, Southampton, UK; Boston: Computational Mechanics Publications, c1997.



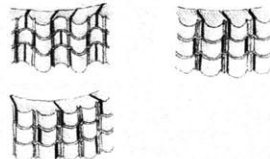




Previous use of brick in the construction of domes, construction details	
Use of stone in the construction of domes I - Stage of inexperience and imitation of brick decoration Shaykh Ahmead Al Qasid, 735/1335 Amir Qaraqoga Al Hasani, before 853/1449 Khawand Tatr al-Higaziyya, 761/1360	
II- Structure in conflict with decoration Amir Tankizbugha , c.760/1350 Amir Tankizbugha , Rabi' c.764/1362 Sultan Shaban, 770/1368-9 Amir Yagay al-Yusufi, 774/1373 Al-Sultaniyya 8th/14th c. Amir Yunis al Dawadar after 783/1381	
III - Decoration and structure first properly coordinated Amir Mahmud AL-Kurdi, 797/1394-5 Sultan Farag ibn Barquq, 803-10/1400-7 (Northern Mausoleum), Amir Ganibak, at madrasa, 830/1426-7 (zig zag decoration)	
IV- Geometrical Problem of adapting overall star pattern interlace Sultan Barsbay, Khankah mausoleum 835/1432 Sultan Barsbay for Amir Ganibak	
V-First essay in Arabesque, return to zig zag Shaykh Abdallah al Manufi,, after 797/1394-95 Amir Gawhar al Qunuqbayi, before 844/1440 Amir, then Sultan, Inal 844/1451	
VI- Mastery, Refinement and luxury Amir, later Sultan Qaytbay, before 879/1474 Sultan Qansuh abu Said 904/1499 Sultan al-Adil Tumanbay 906/1591 <u>Amir Khayrbak 908/1502</u>	

Table 3 Table constructed upon Christel Kessler classification for the different periods in the mastery of dome construction and decoration. Source: "The Carved Masonry Domes of Mediaeval Cairo", The American University in Cairo Press, Cairo 1976.

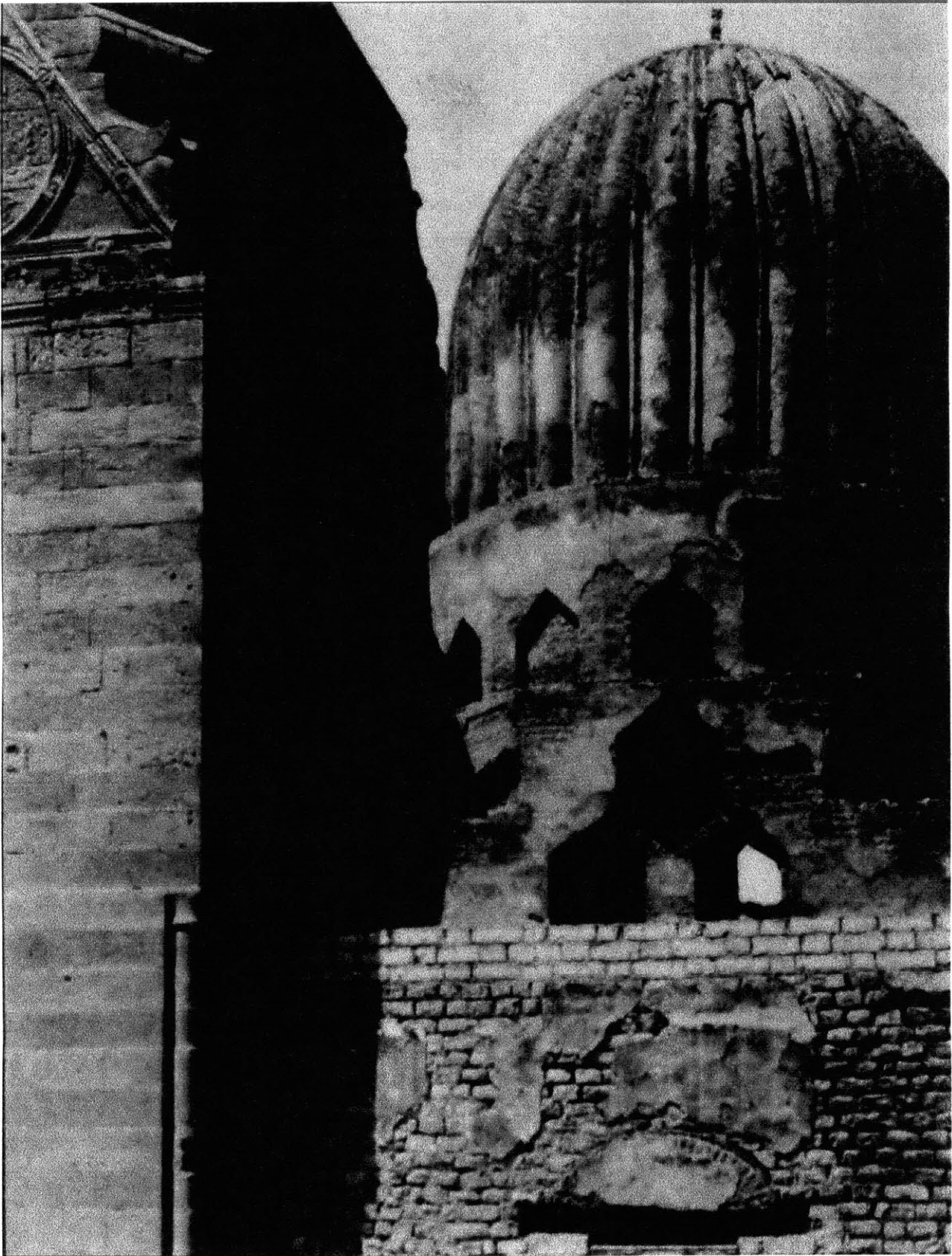


Fig. 1.1 Cairo, Mausoleum of As-Sawabi, 1285 A.D.

© Creswell Archive, Ashmolean Museum, neg. Image courtesy of Fine Arts Library, Harvard College Library

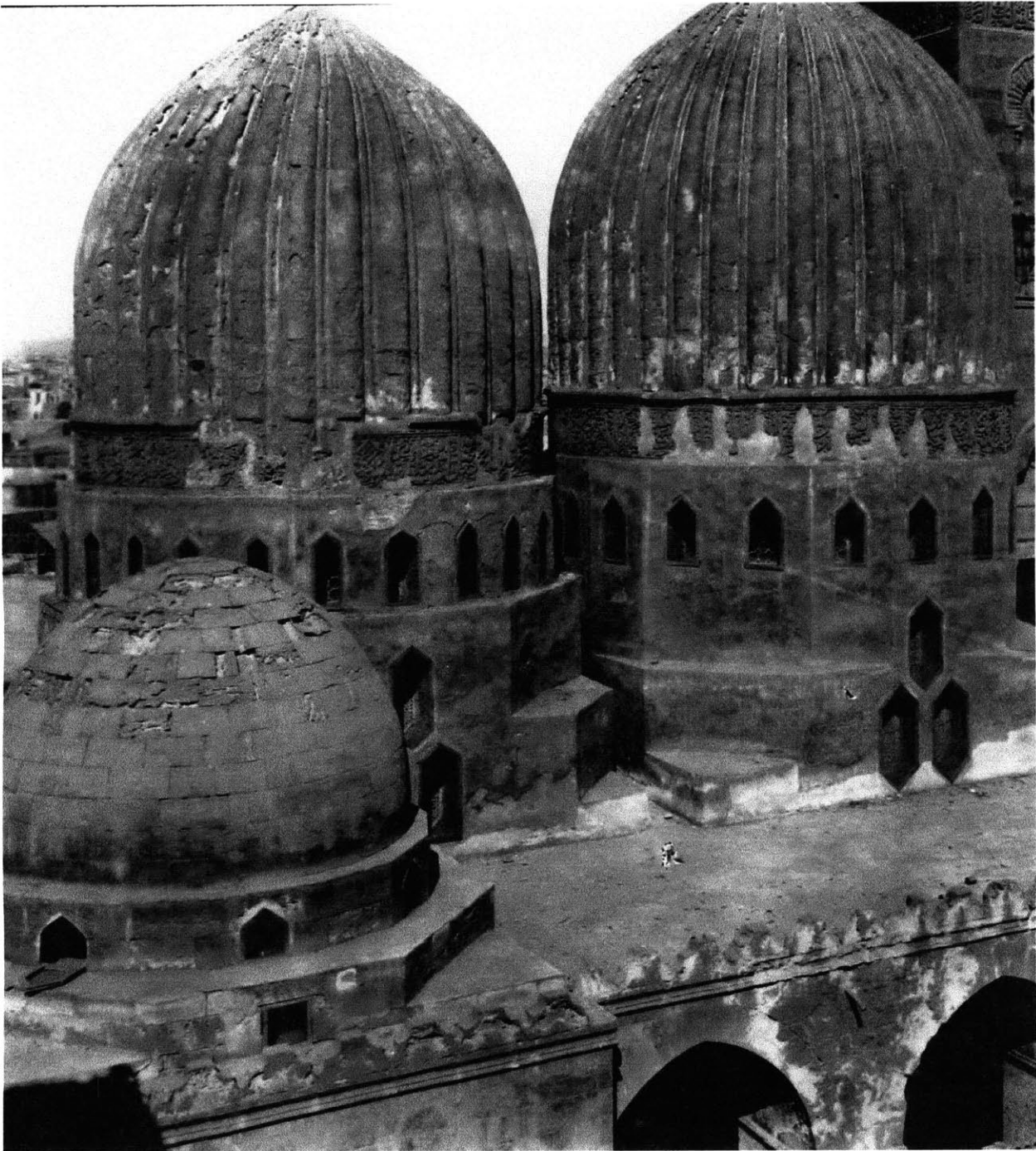


Fig. 1.2 Cairo, Mosque of Salar and Sangar al Gawli 1303-4 A.D.

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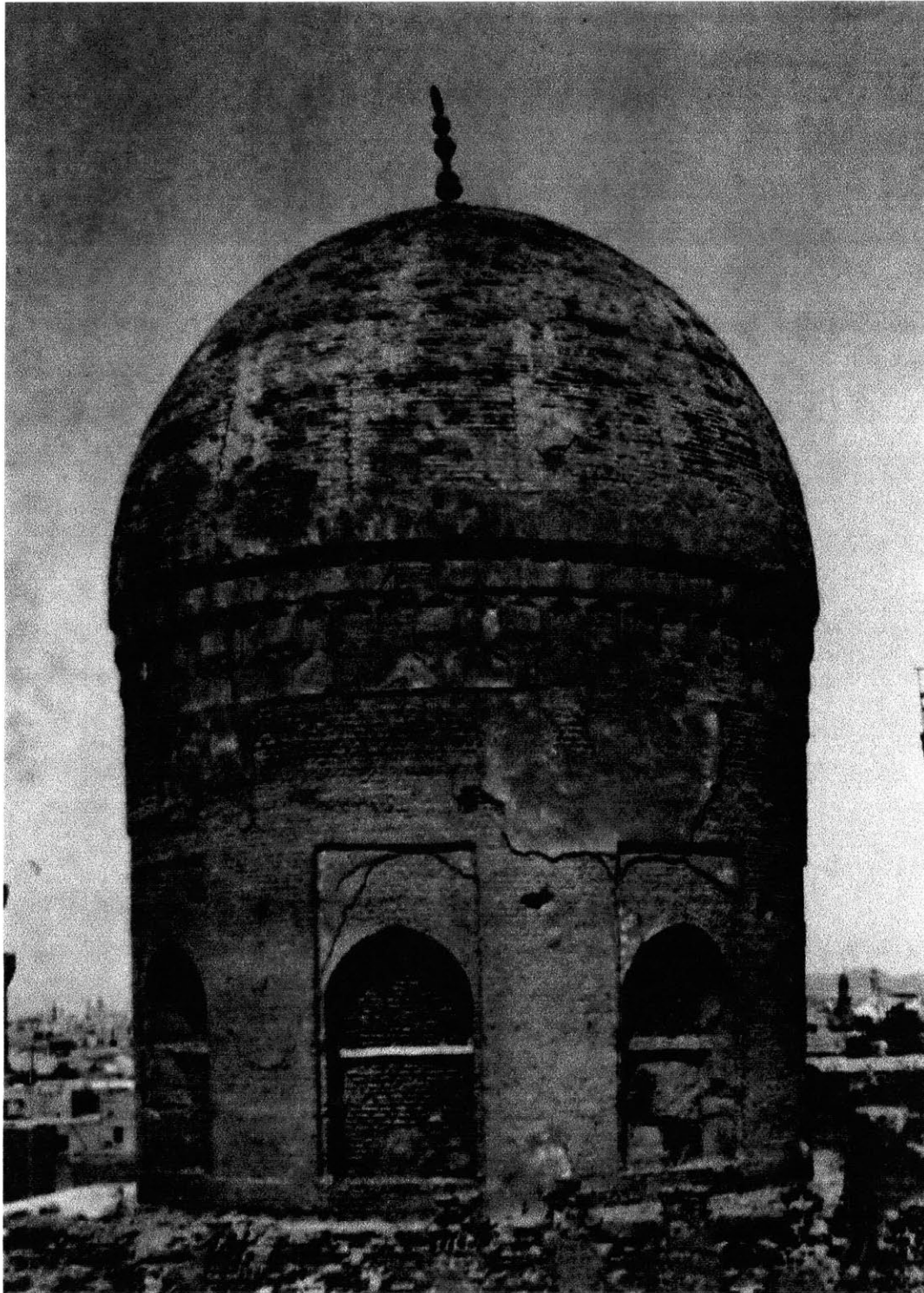


Fig. 1.3. Dome of the Madrasa of Sarghatmish, 1356 A.D..

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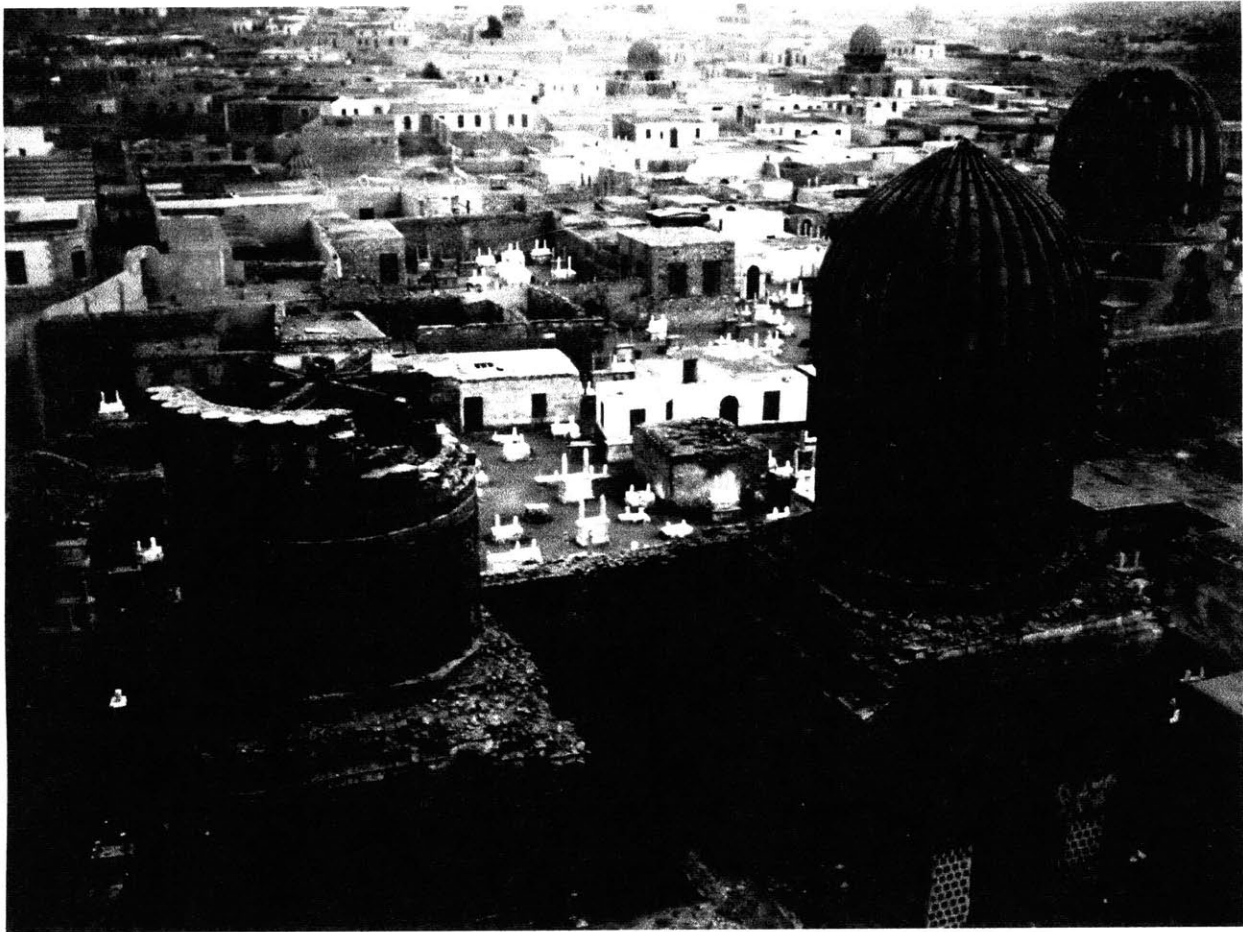


Fig. 1.4 Al-Sultaniyya Mausoleum 1350s-1360s A.D.

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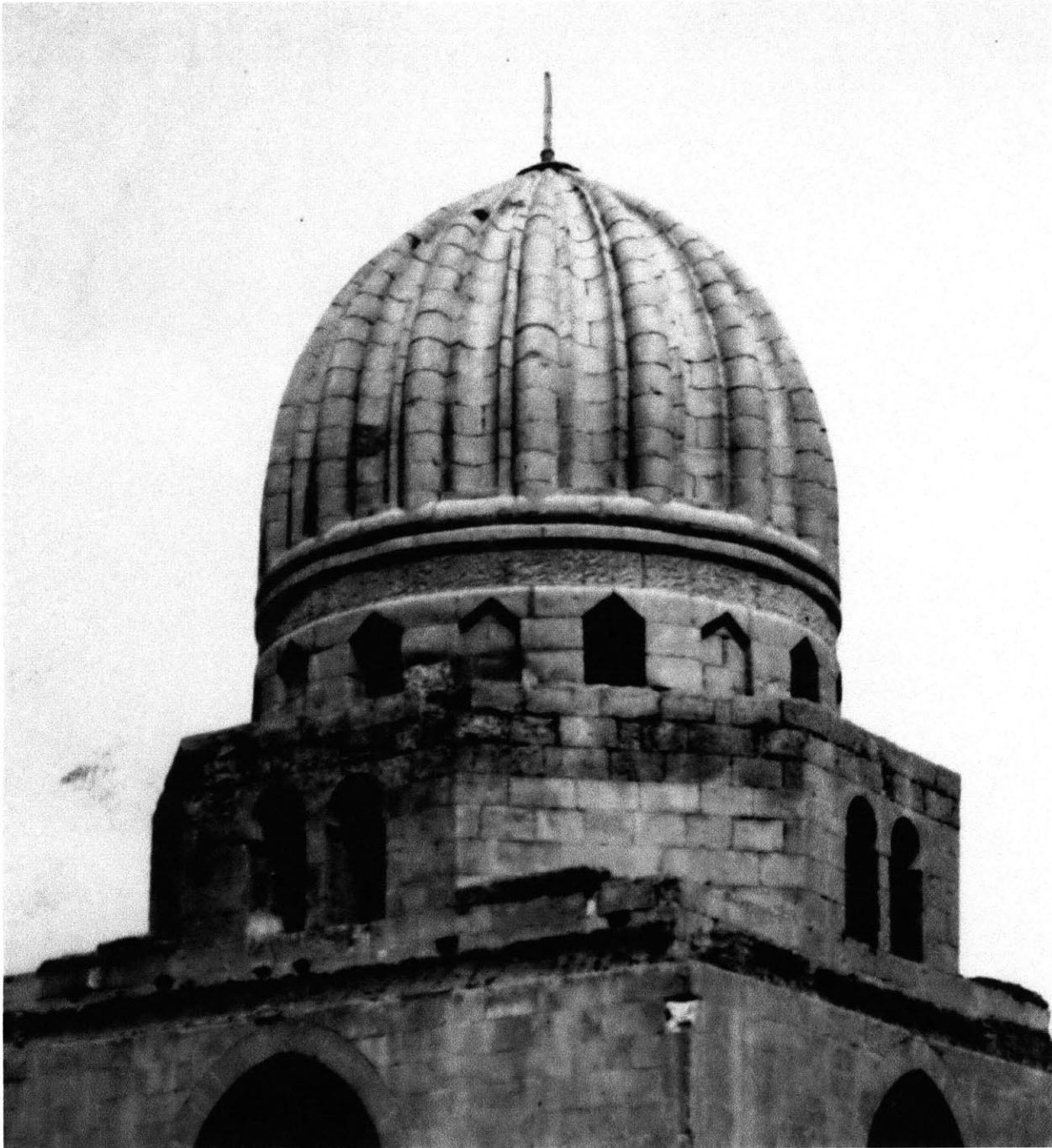


Fig. 1.5 Amir Tankizbugha Mausoleum 1359 A.D.

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Fig. 1.6 Amir Tankizbugha Mausoleum interior of the dome 1359 A.D.
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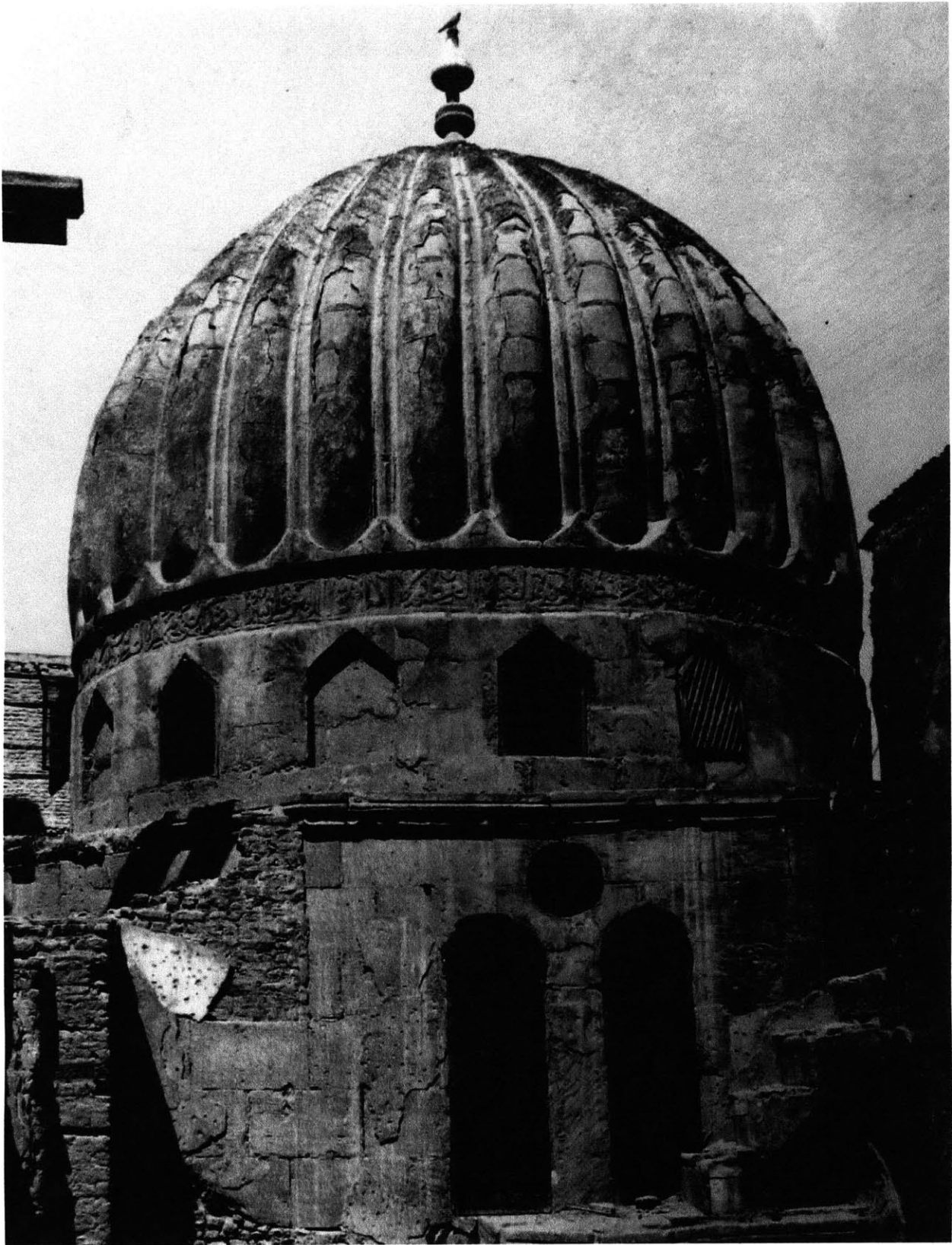


Fig. 1.7 Tatar al-Hijaziya Funerary Complex 1360A.C.

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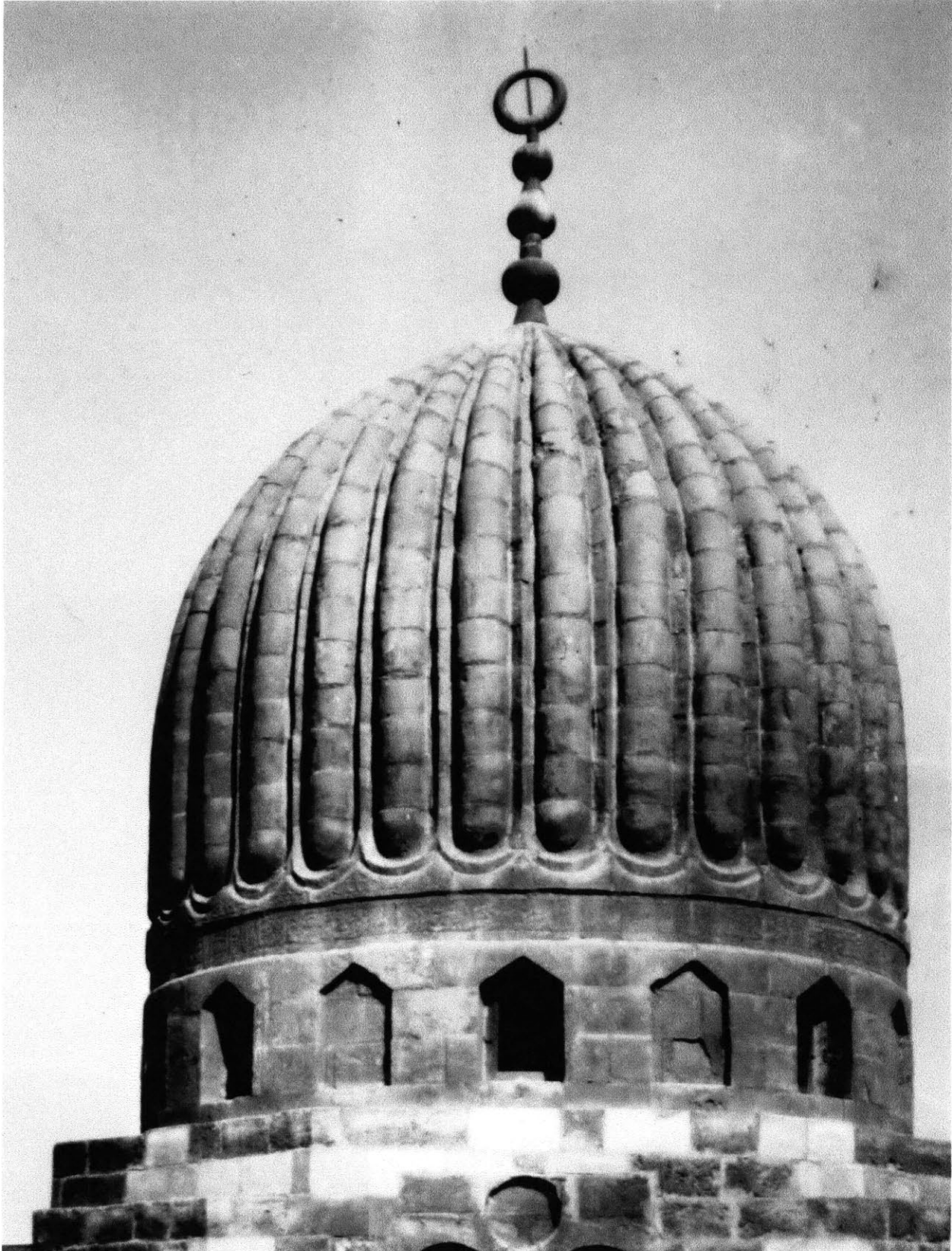


Fig. 1.8 Umm al-Sultan Sha'ban Madrasa 1369 A.D.(North Eastern dome)

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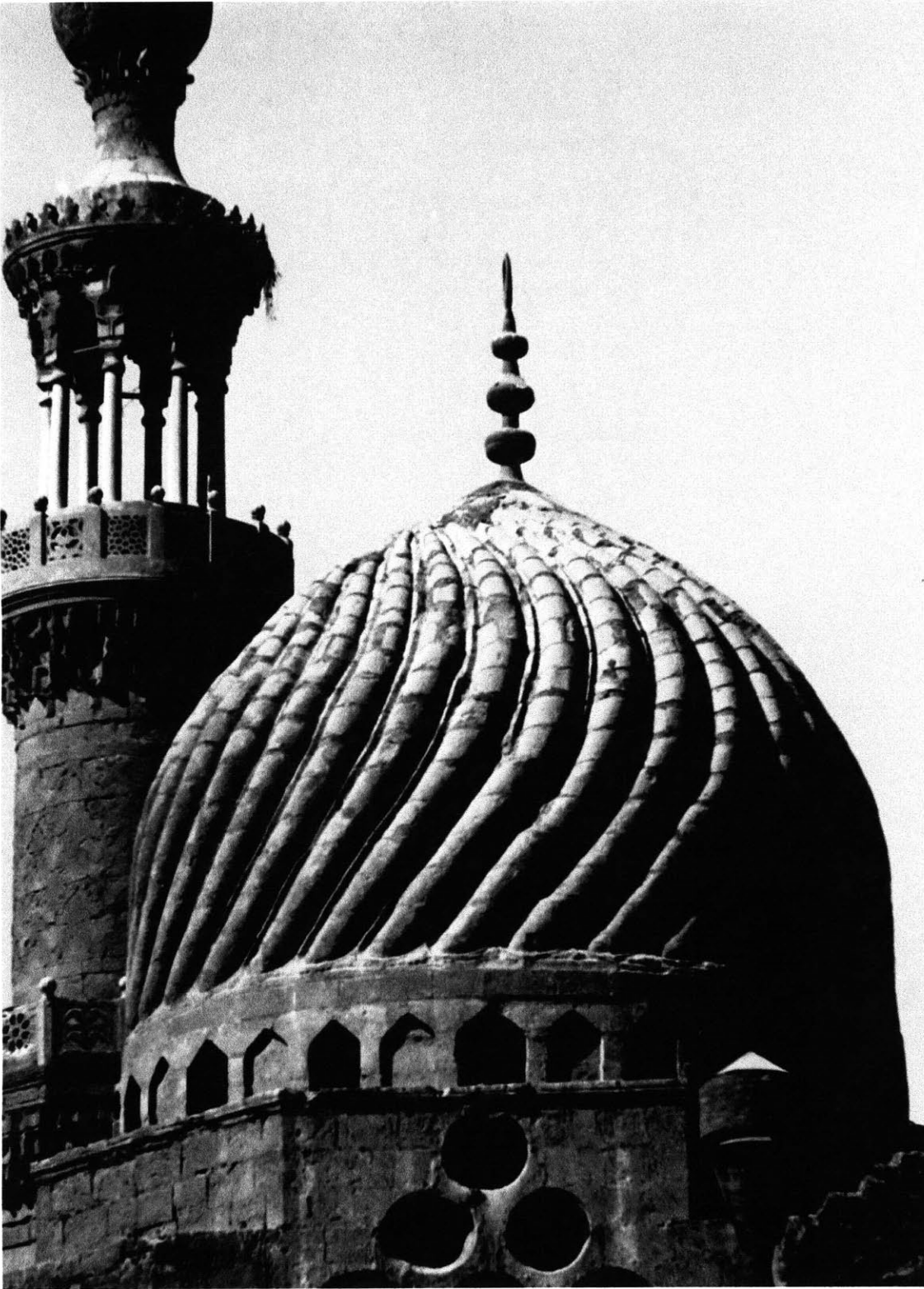


Fig.1.9 Amir Ylgay Al Yusufi 1373 A.D.

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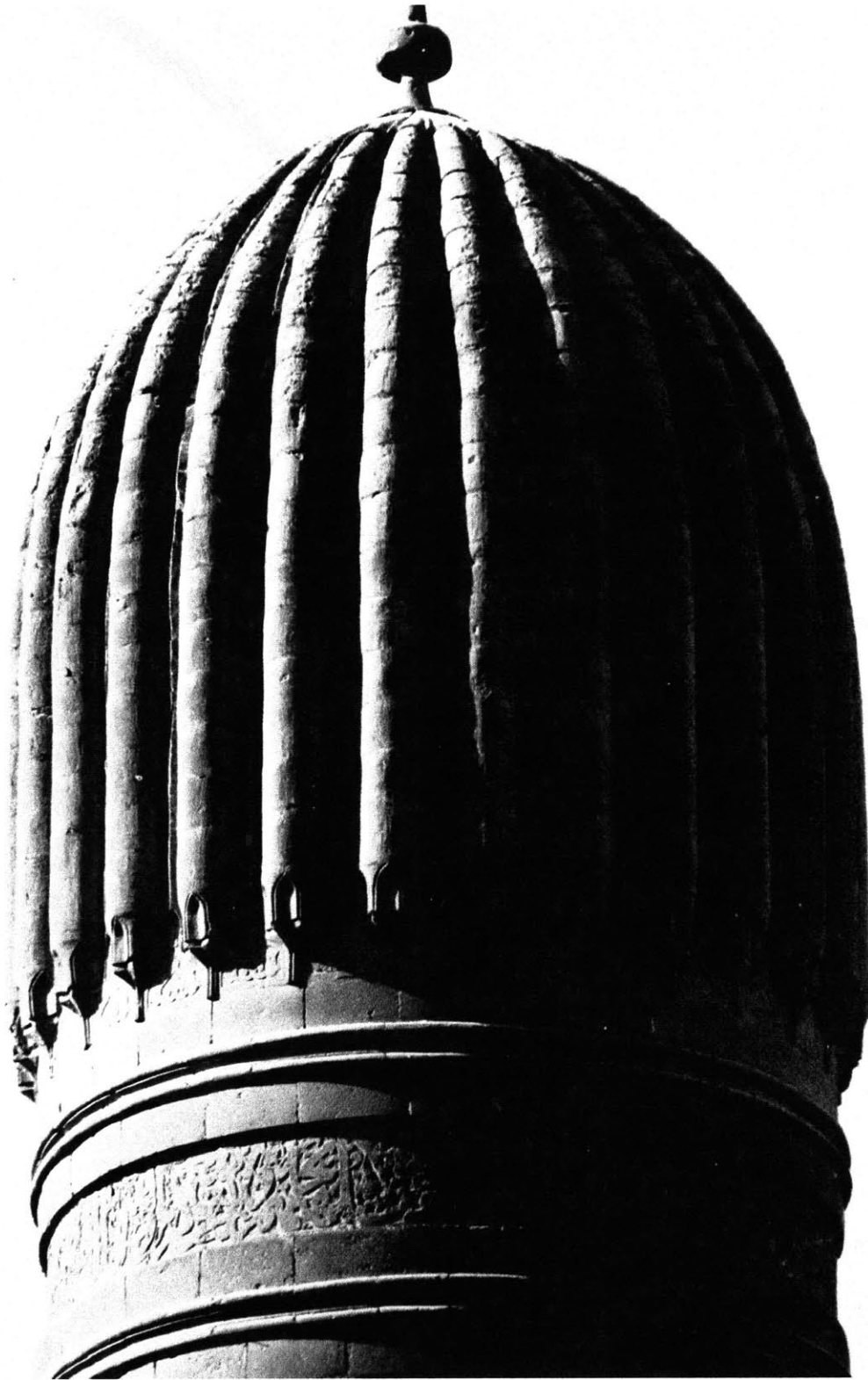


Fig. 1.10 Yunus al-Dawadar Mausoleum 1382 A.D.

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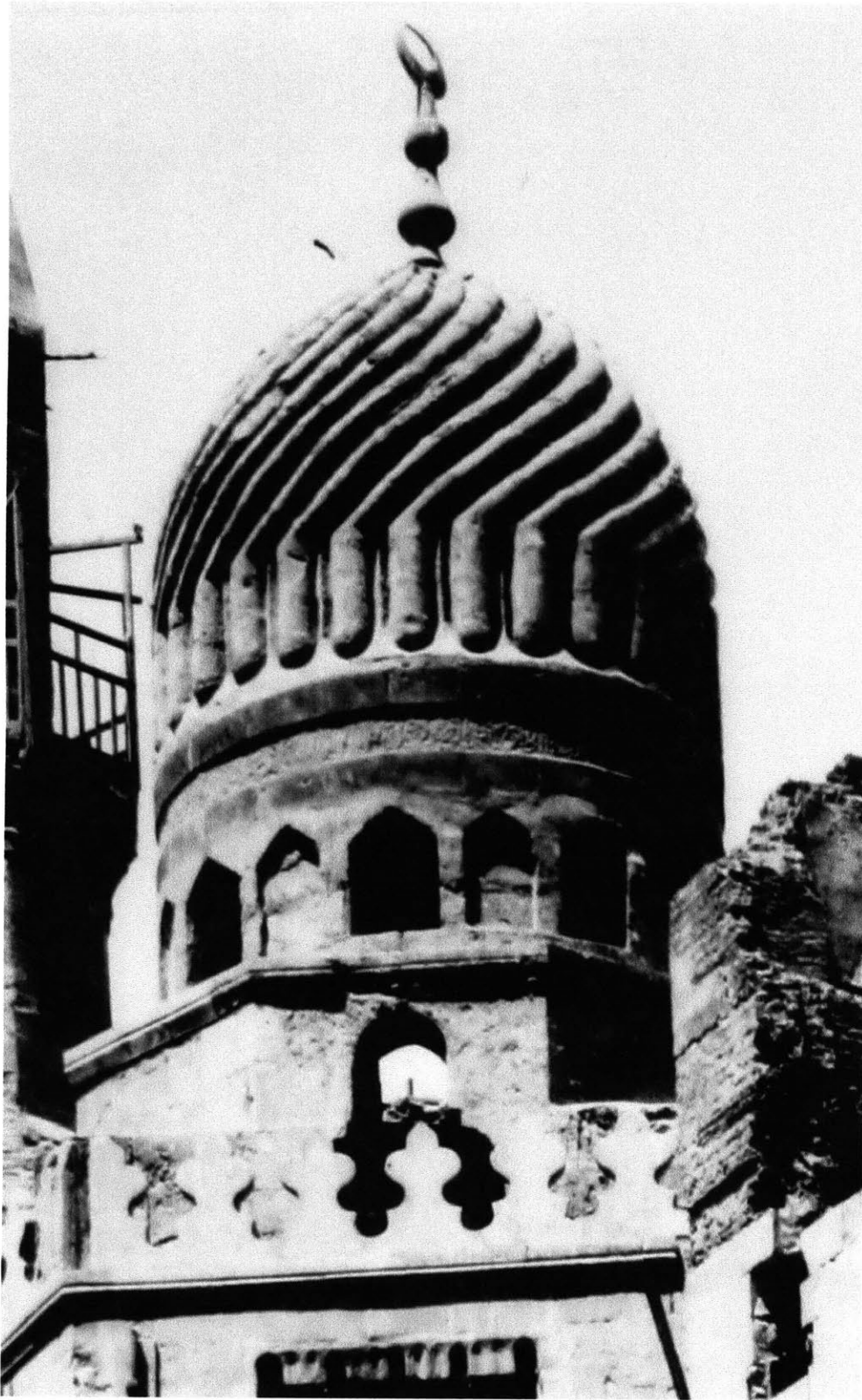


Fig. 1.11 Mosque of Aytmish Al Bagashi 1383 A.D.

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Fig. 1.12 Mosque of Inal Al Atakbi 1392-1393 A.D.(dome)

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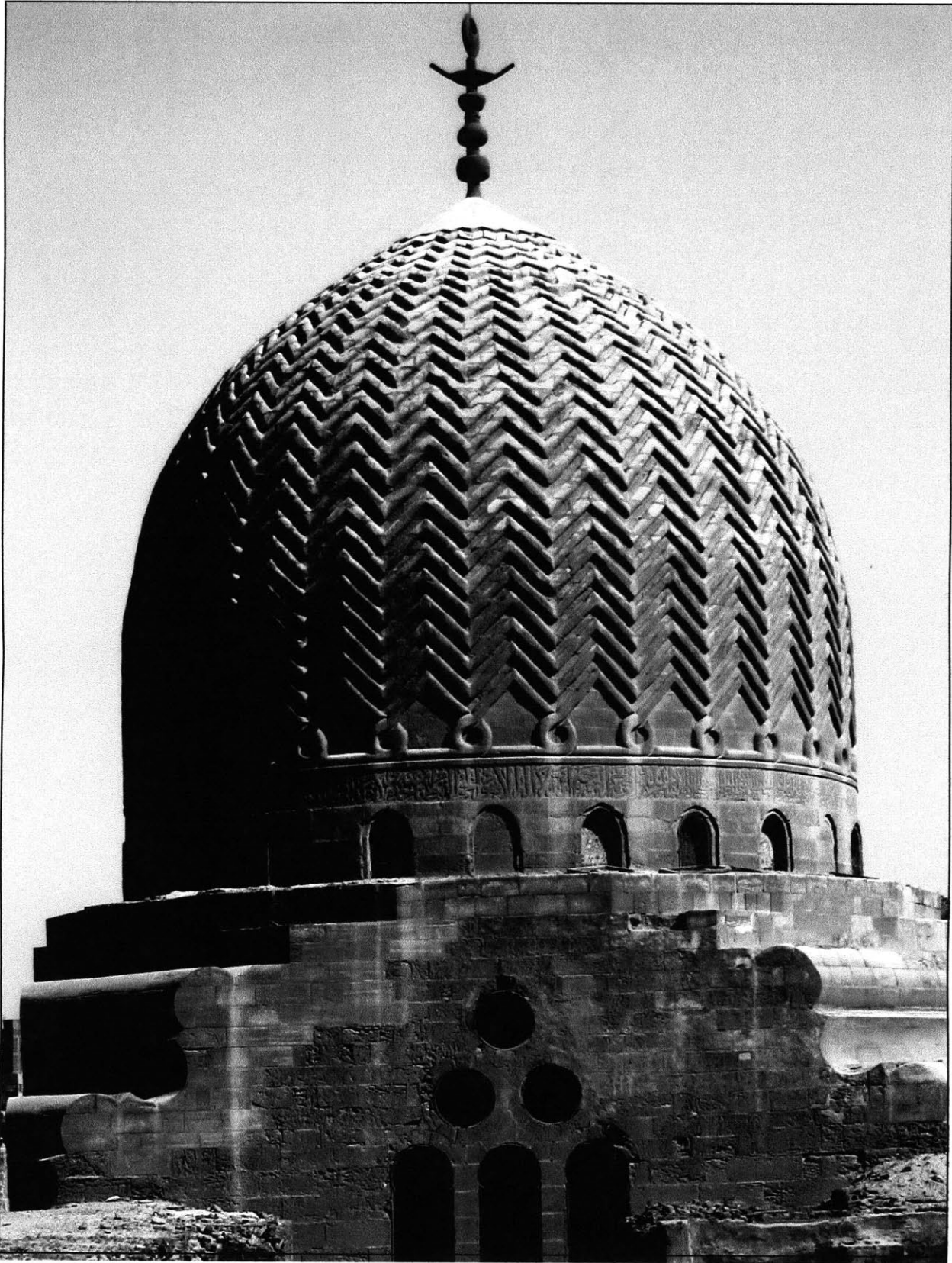


Fig. 1.13 Complex of Farag Ibn Barquq 1389-1411 A.D.
Photo by the author



Fig. 1.14 Qanibay al-Muhammadi Mosque 1403 A.D.

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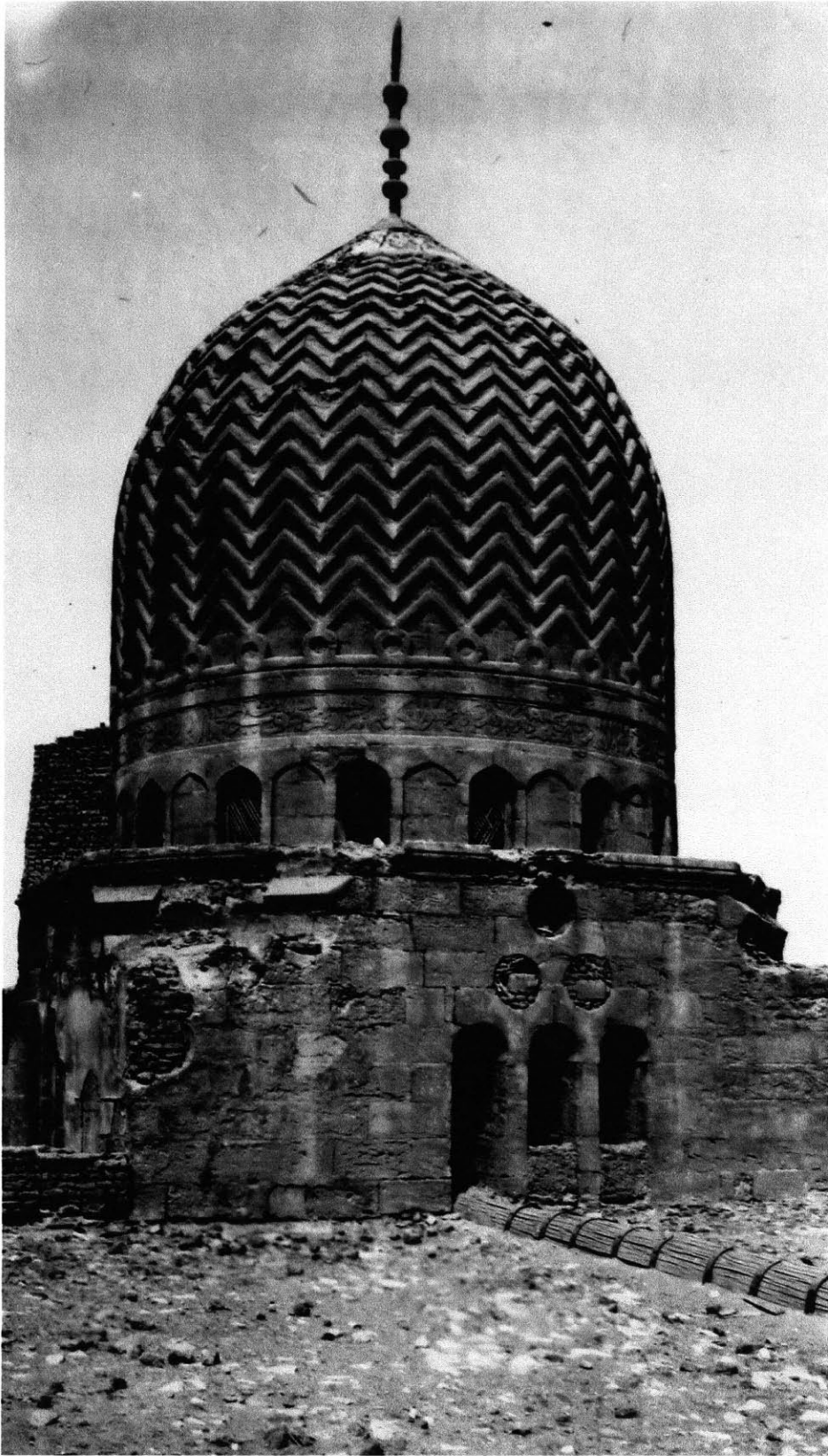


Fig. 1.15 Mosque of Sultan Barsbay 1423-24 A.D.

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Fig. 1.16 Mausoleum of Khadiga Umm al-Ashraf 1430-1440 A.C.
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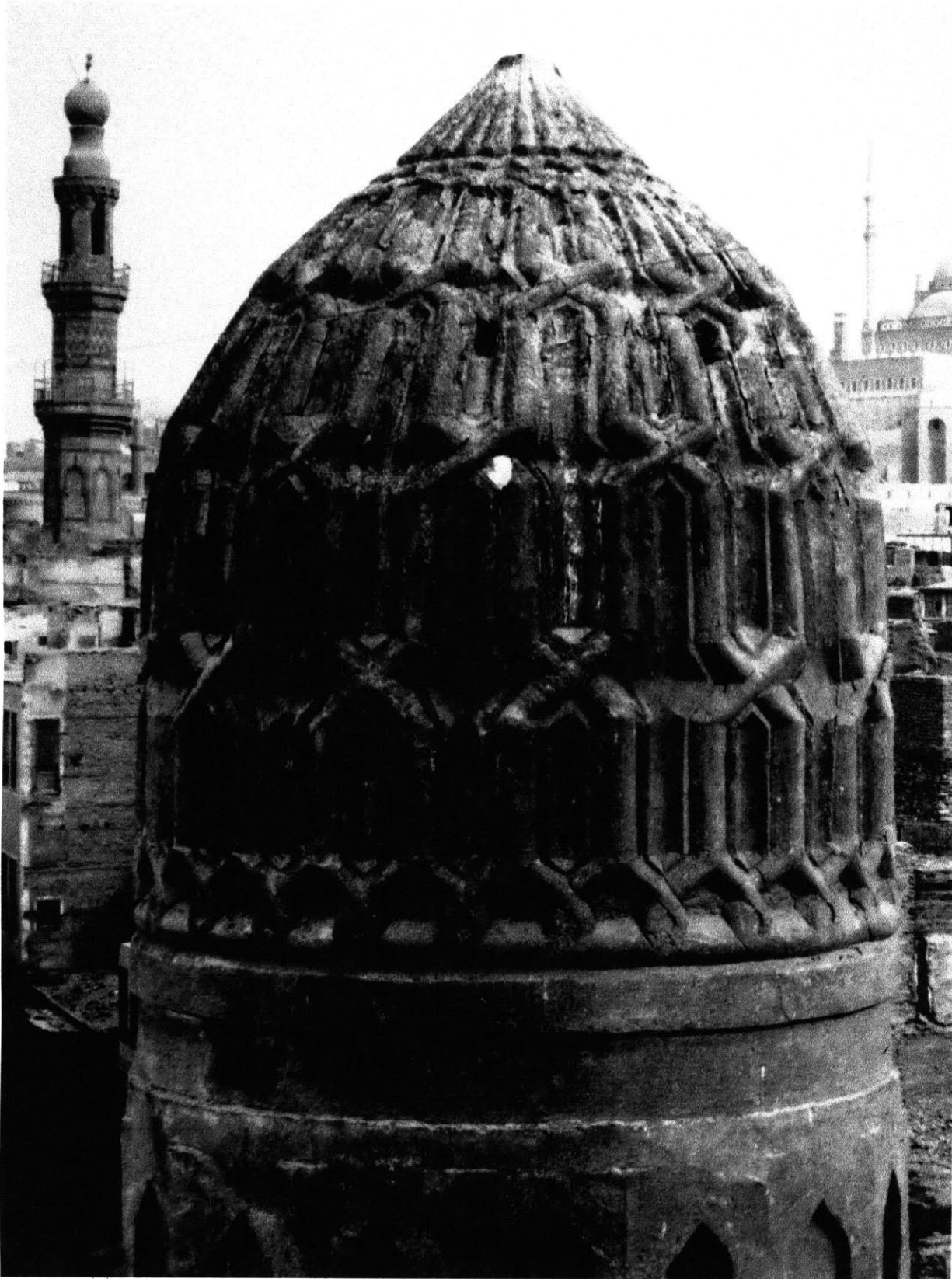


Fig. 1.17 Amir Taghribardi Funerary Complex 1440 A.D.(Dome)

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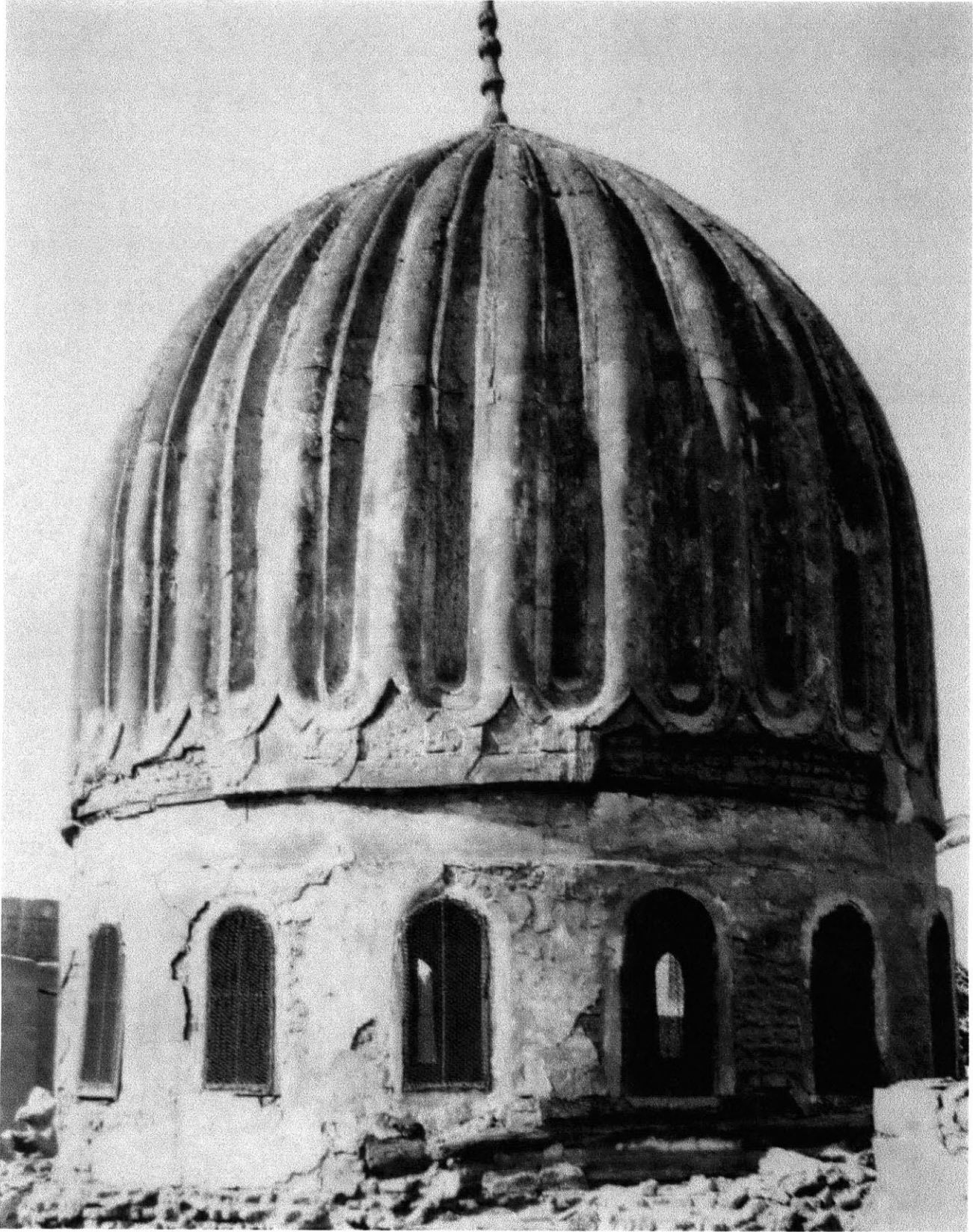


Fig. 1.18 Cairo, Mausoleum of Sudun al- Gasrawi 1460-67 A.D.

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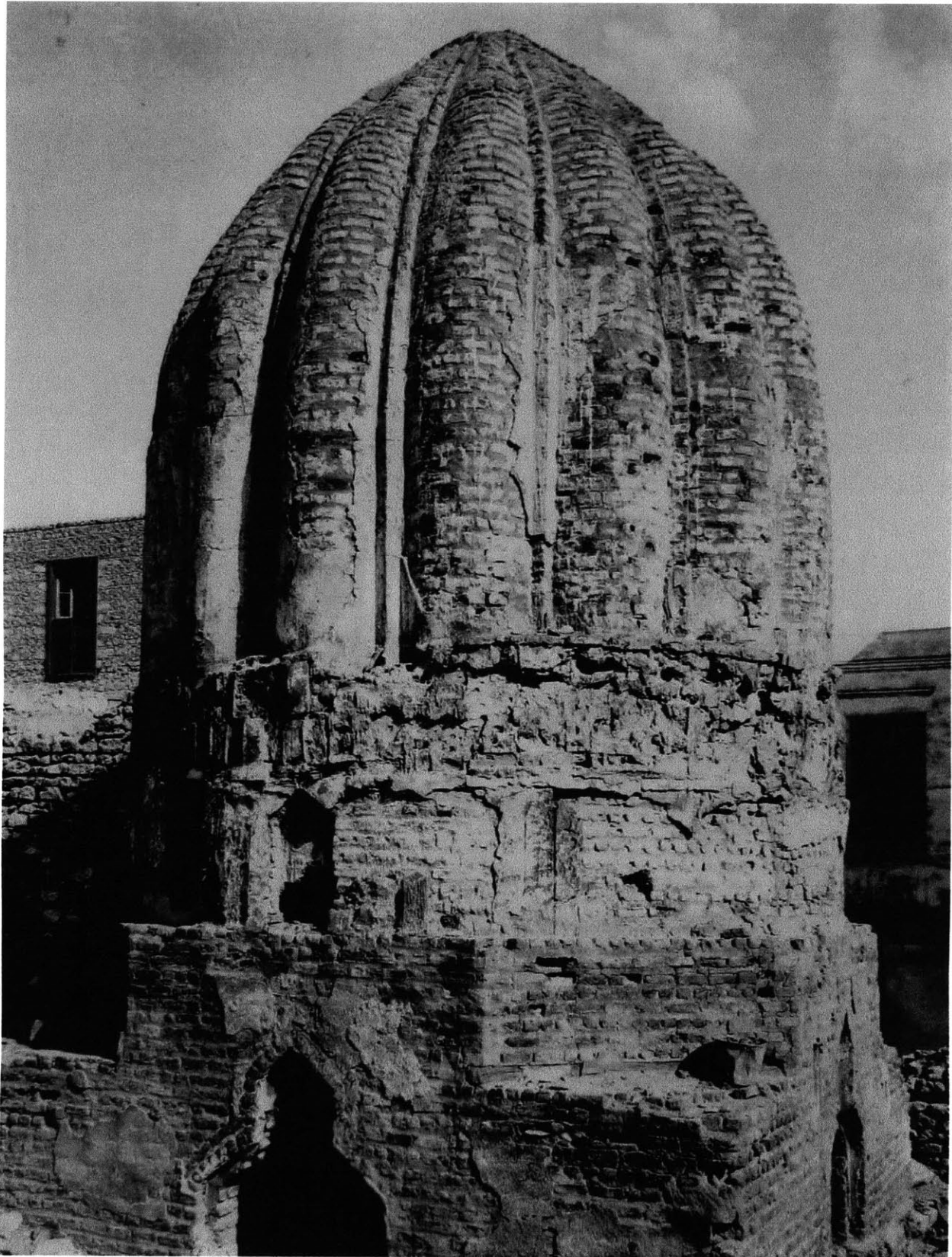


Fig. 1.19 Cairo, Khanqah of Sa'd ad-Din ibn Ghurab, 1406 A.D.

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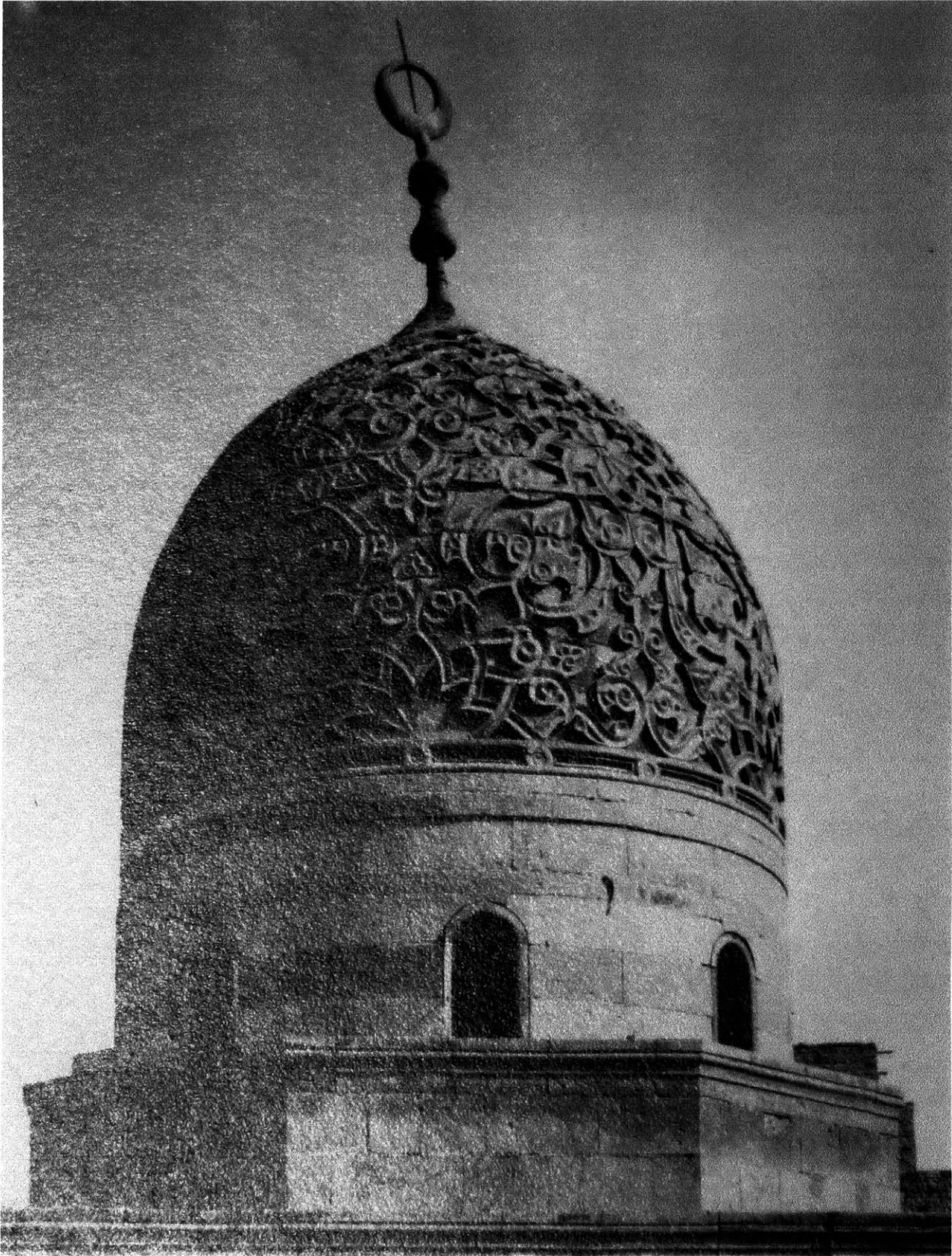


Fig. 1.20 Cairo, Mausoleum of Al-Gushani 1495 -96 A.D.

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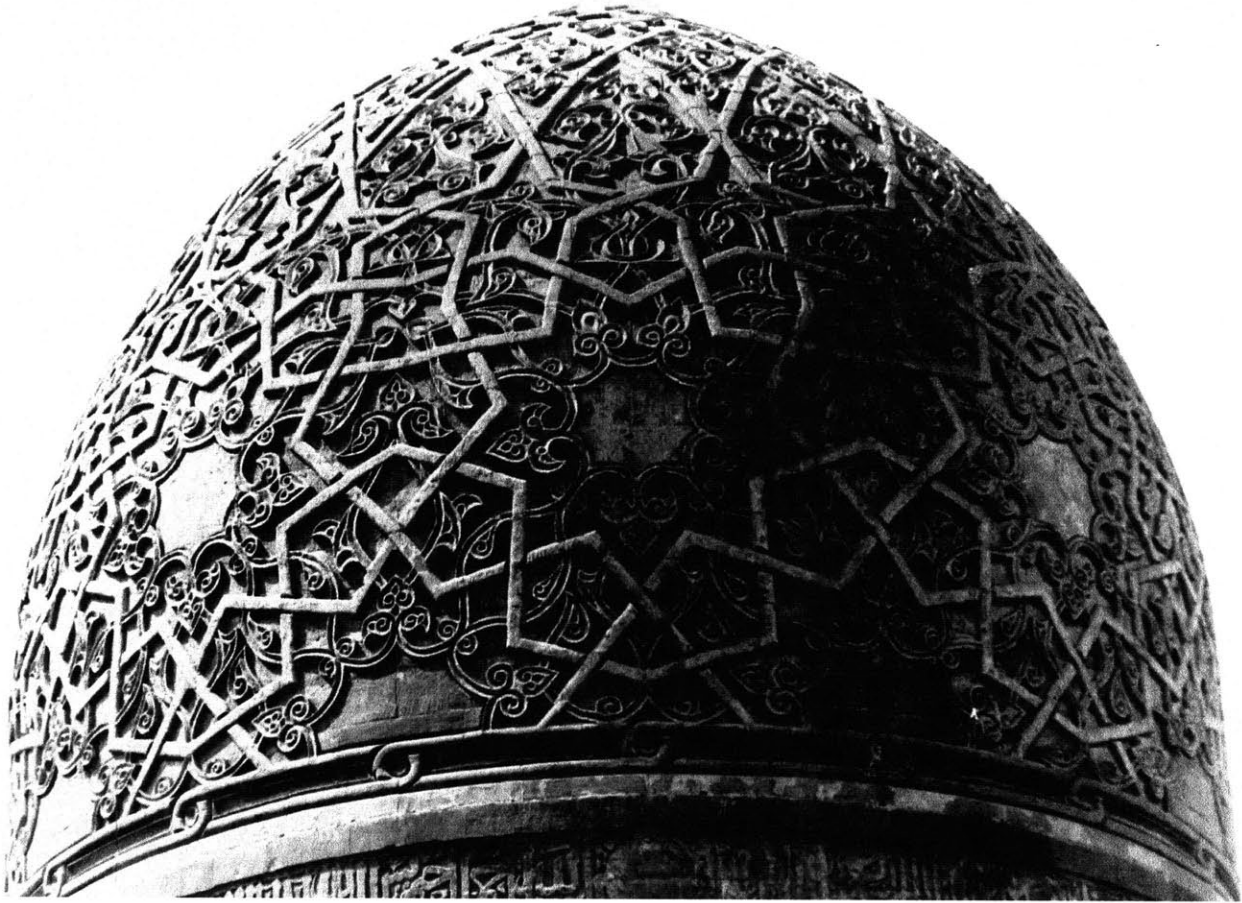


Fig. 1.21 Cairo, Sultan Qaytbay Funerary Complex 1472-1474 A.D.

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Fig. 1.22
Sultan Qansuh Abu Sa'id Mausoleum 1499A.D. Photo by F.Yegul
Image courtesy of Fine Arts Library, Harvard College Library

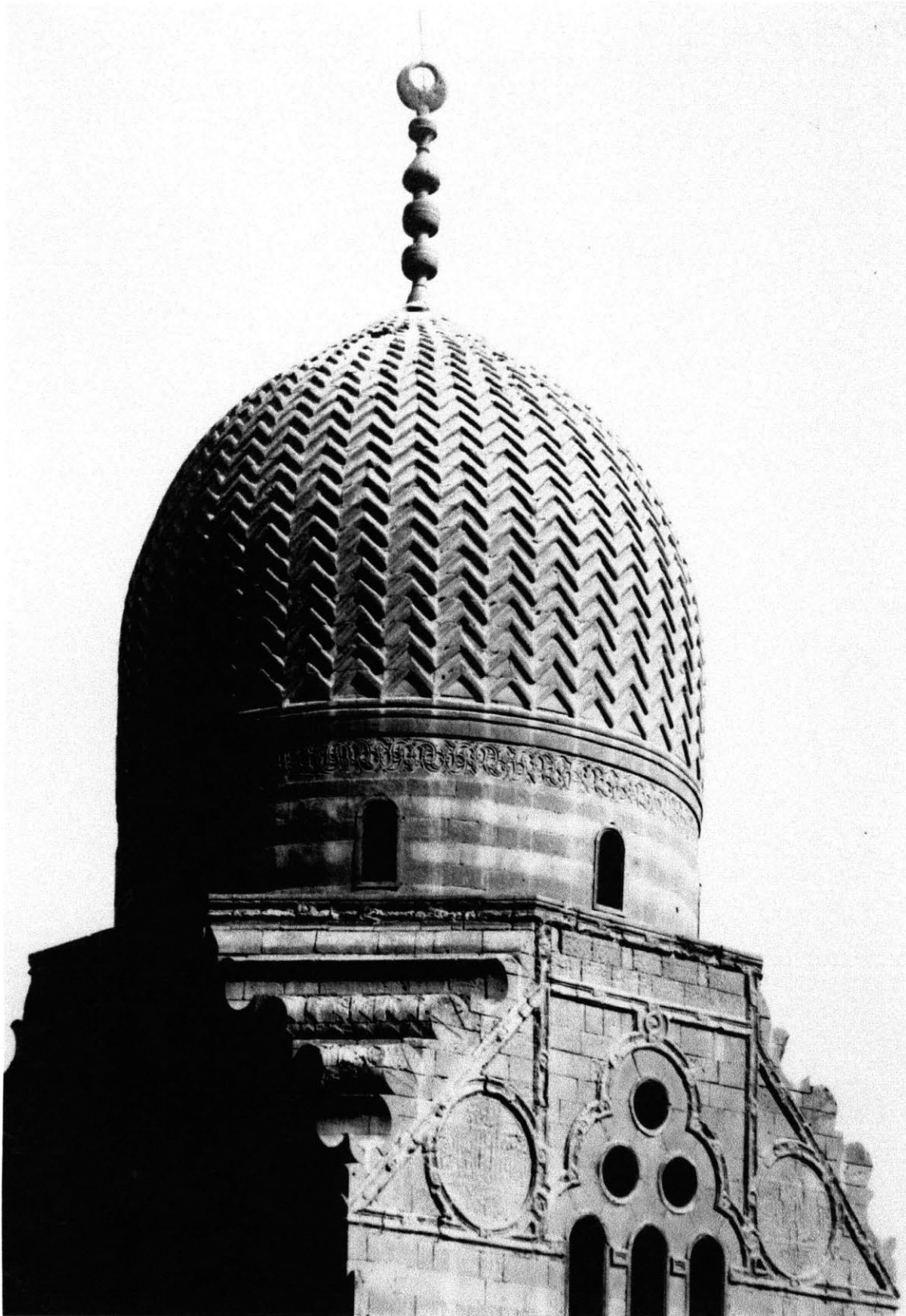


Fig. 1.23
Amir Tarabay al-Sharifi Funerary Complex 1503-4 A.D.(dome)

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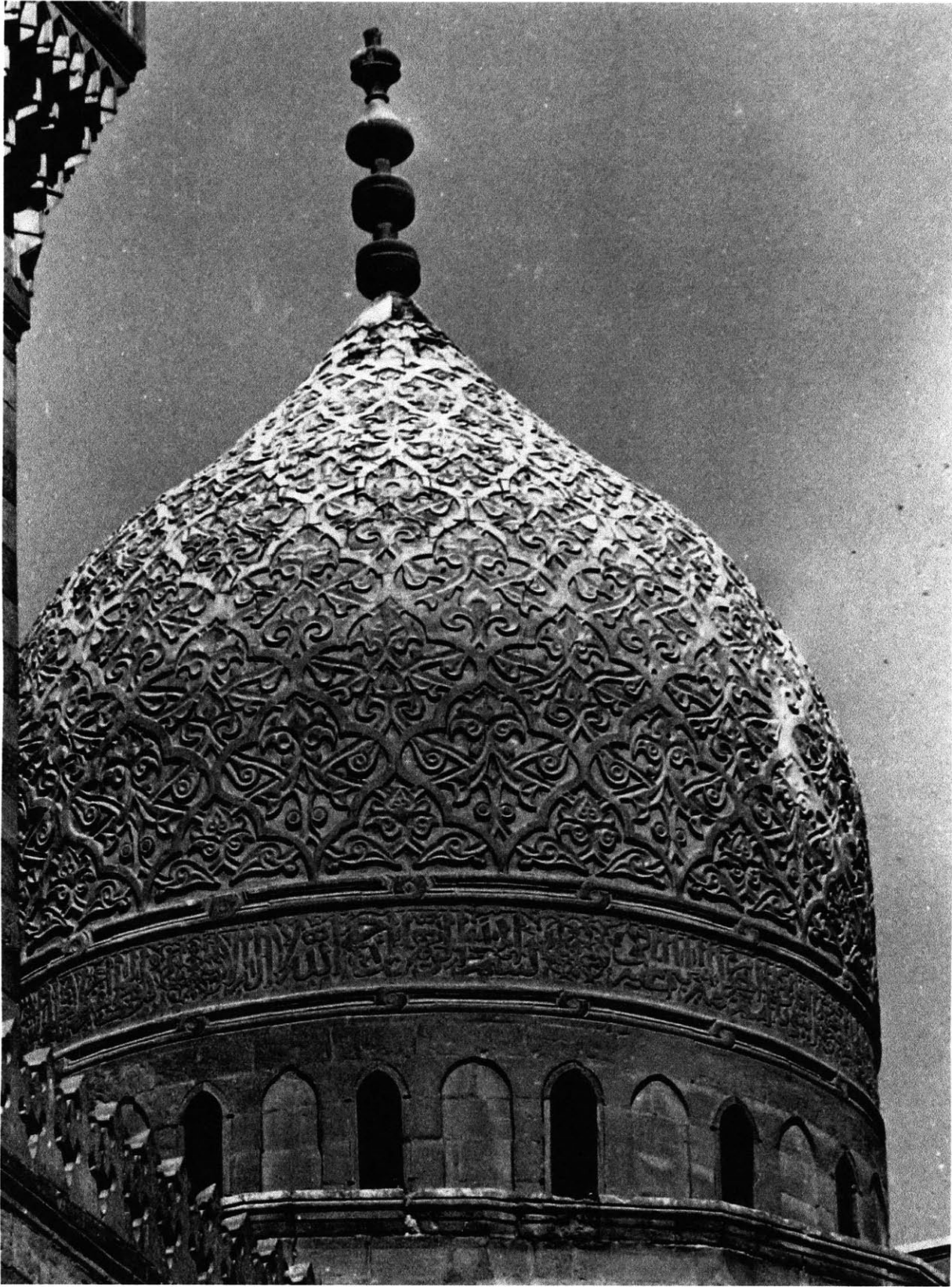


Fig. 1.24 Amir Akhur Qanibay Mosque 1503 A.D. dome

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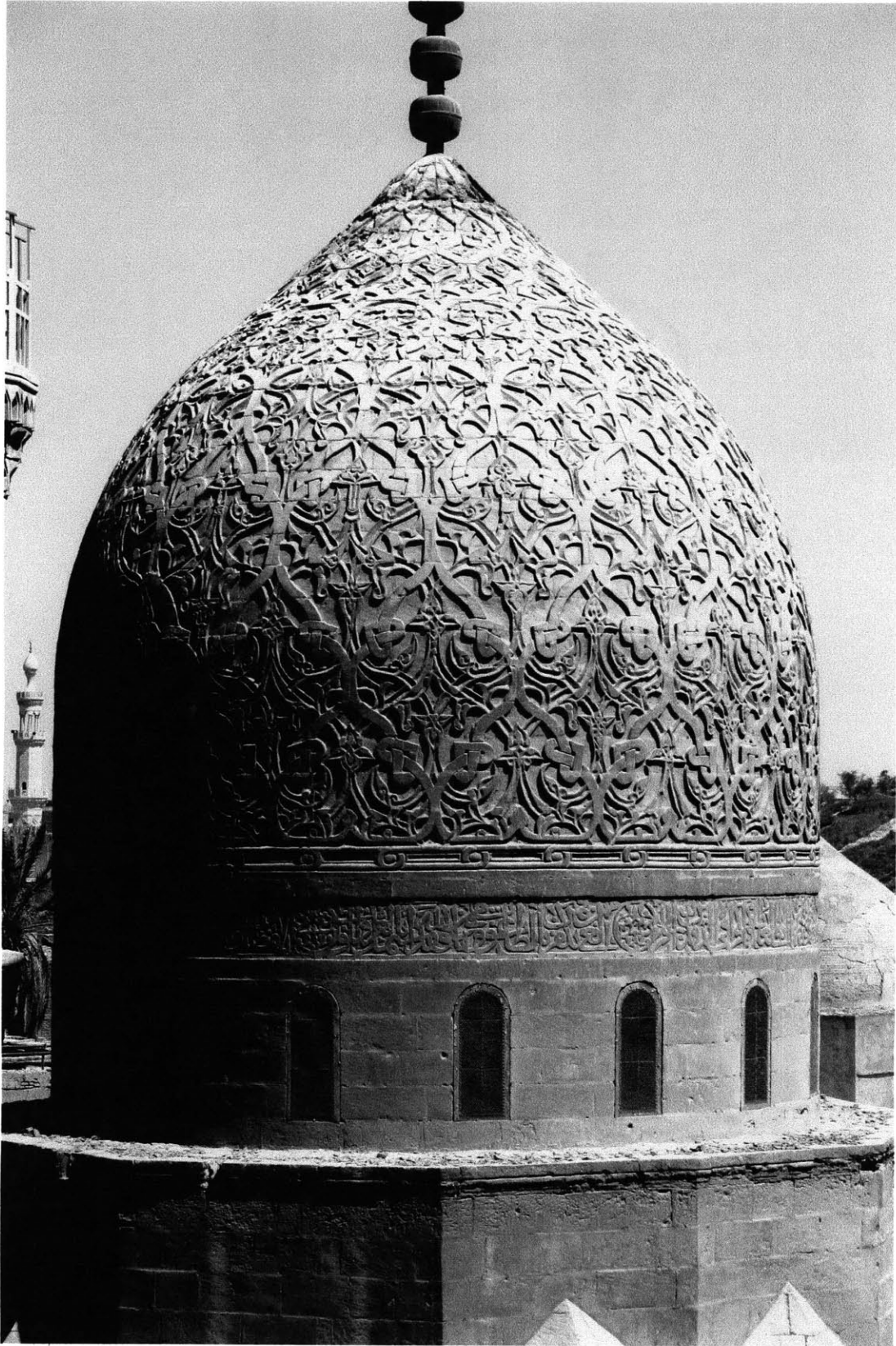


Fig. 1.25 Cairo, Mausoleum of Amir Khayer Bek (1502 A.D.)

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Fig. 1.26 Cairo, Mausoleum of Azrumuk 1503-1504 A.D.(dome)

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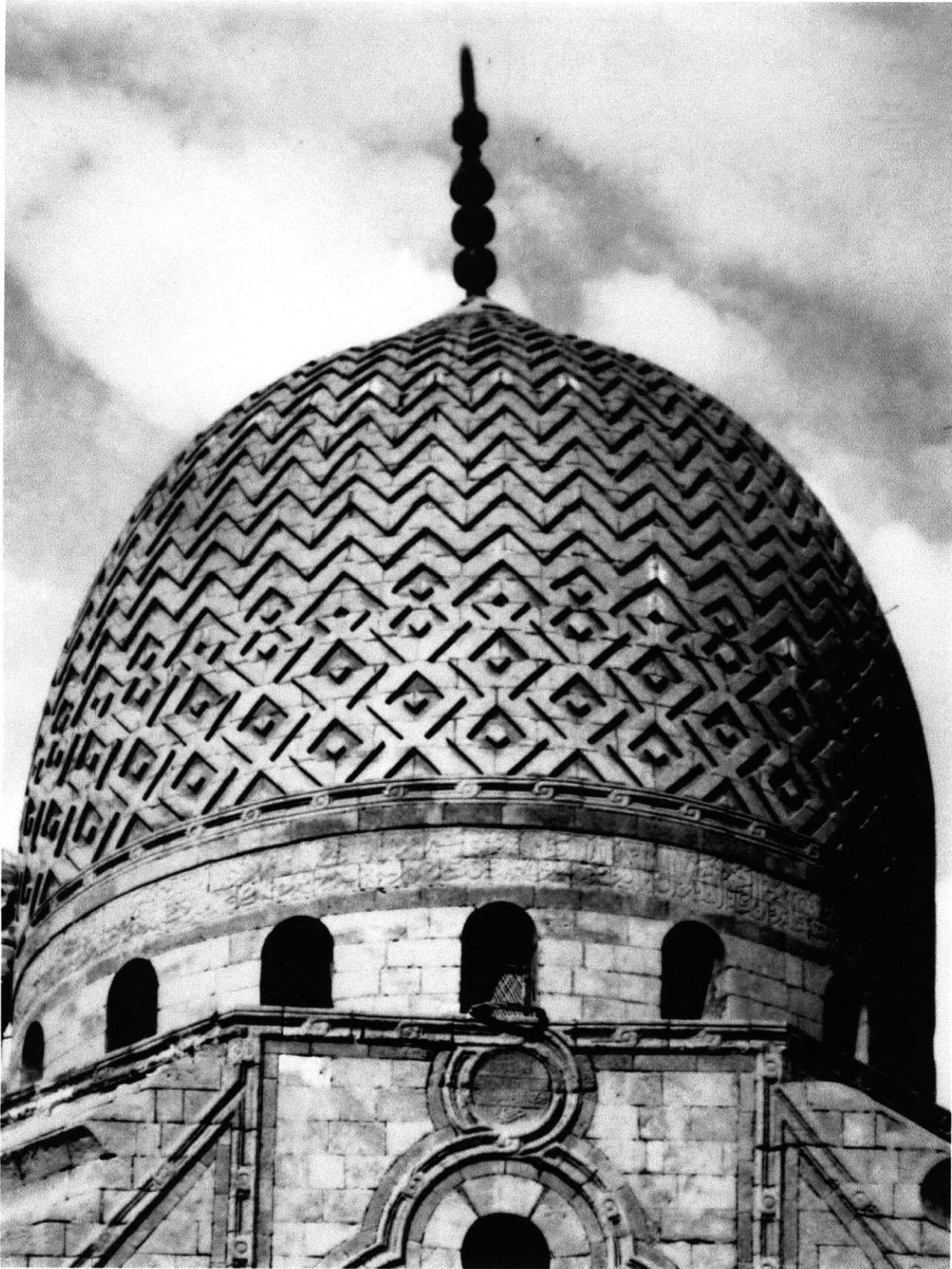
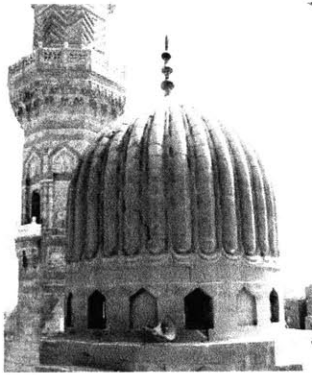


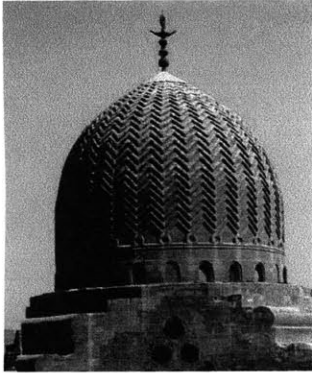
Fig. 1.27 Cairo, Amir Qurqumas Funerary Complex 1506 A.D. (dome)

© Creswell Archive, Ashmolean Museum, neg. Image courtesy of Fine Arts Library, Harvard College Library


Chapter 2 (Images)
Methodology

	Total height of the dome including the drum	Internal diameter	Section at the drum	Section at the top
	6.60 m	5.30m	0.33m	0.75m

Umm Sultan Sha'Ban

	14.77m	14.43m	0.33m	0.94m
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Frag Ibn Barquq

	10.12m	7.46 m	0.44m	1.08m
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Khayer Bek

Table 4
Comparative table of the general dimensions of the three stone domes of Umm Sultan Sha;ban, Farag Ibn Barquq and Amir Khayer Bek

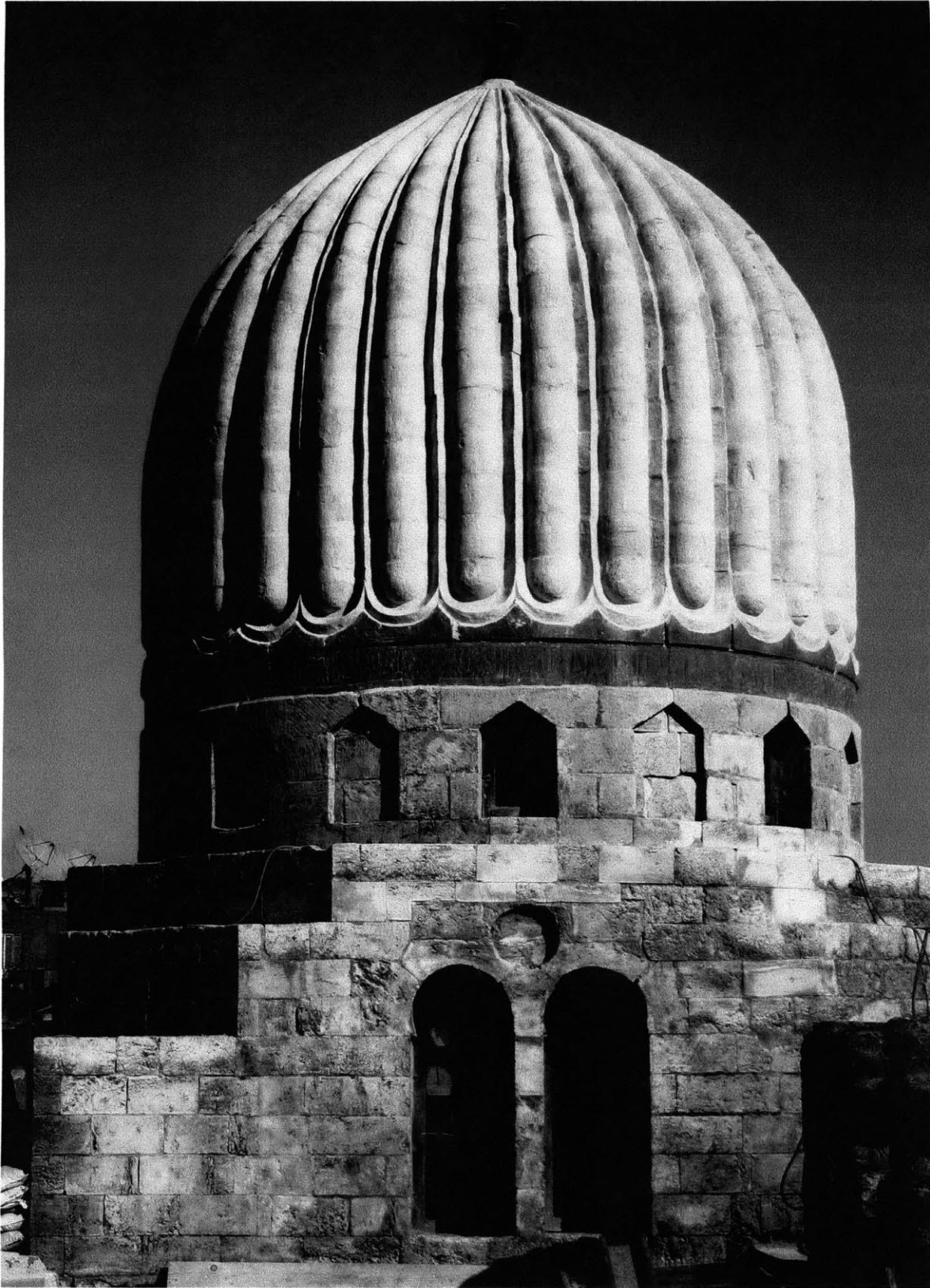


Fig. 2.1 Mausoleum of Umm Sultan Sha'ban 1369 A.D (Intramuros Islamic Cairo)
Photo by the author

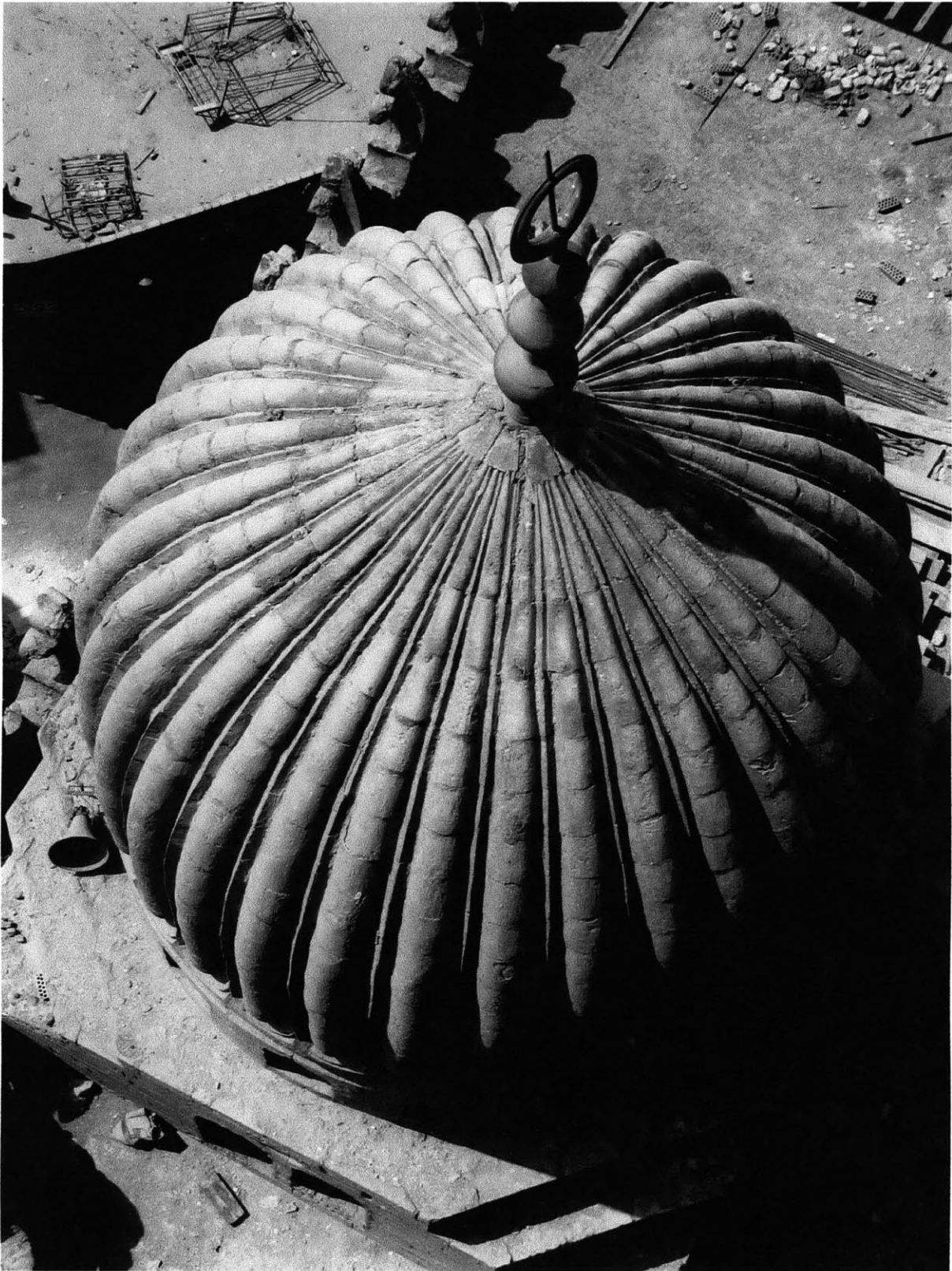


Fig. 2.2 Mausoleum of Umm Sultan Sha'ban, aerial view.. The ashlars constituting the rings are very evident.
Photo courtesy of the Aga Khan Trust for Culture



Fig. 2.3 Interior of the Mausoleum of Umm Sultan Sha'ban. The ashlars constituting the rings are very evident also in the interior.
Photo by the author



a)



b)



c)

Fig. 2.4 Restoration work at the Mausoleum of Umm Sultan Sha'ban. The pictures show that the crescent is hollow and it is held by a wood post that is embedded in the dome top part. Photos courtesy of the Aga Khan Trust for Culture

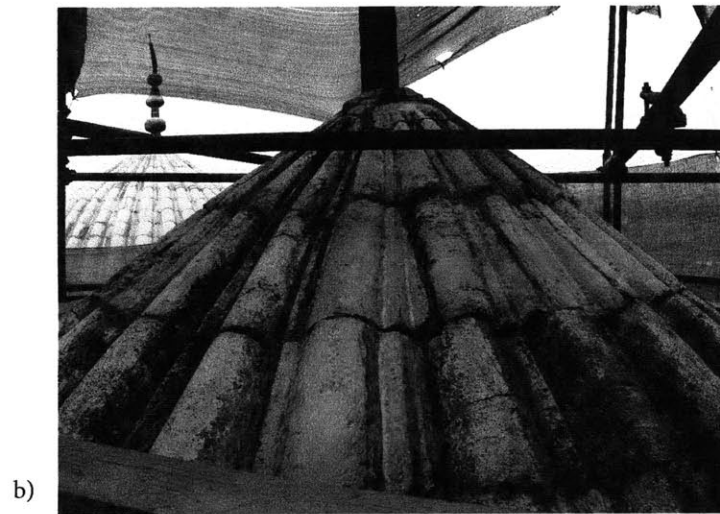
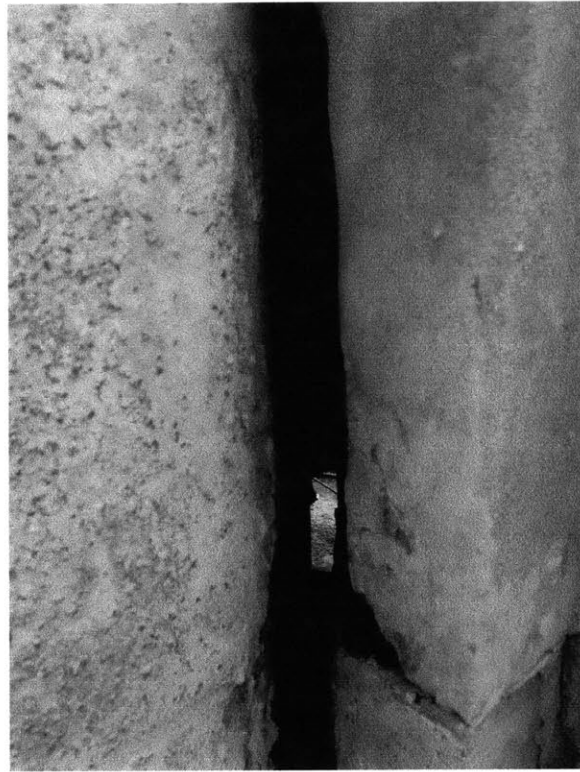


Fig. 2.5 Restoration work at the Mausoleum of Umm Sultan Sha'ban, picture of the second dome, the small one. The pictures show a detail of the same system of wood post holding the crescent in the dome upper part.



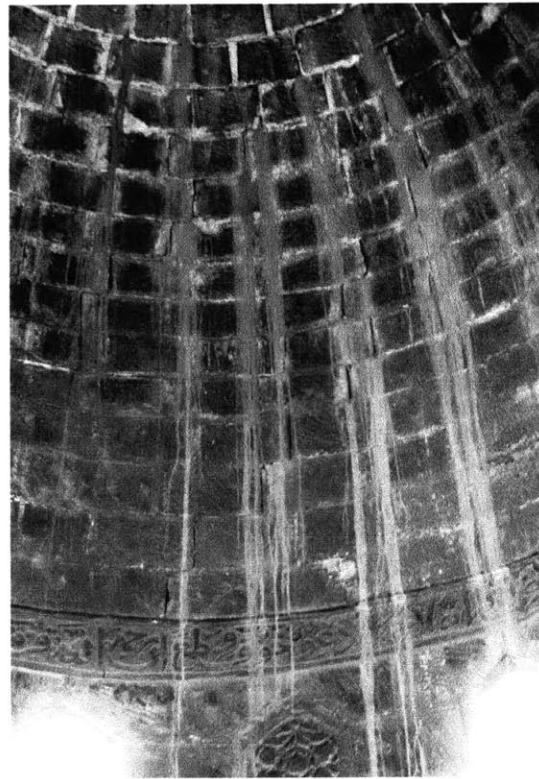
a)



b)



c)



d)

Fig. 2.6 Restoration work at the Mausoleum of Umm Sultan Sha'ban. The pictures show the external and internal step-like cracks. Photos courtesy of the Aga Khan Trust for Culture

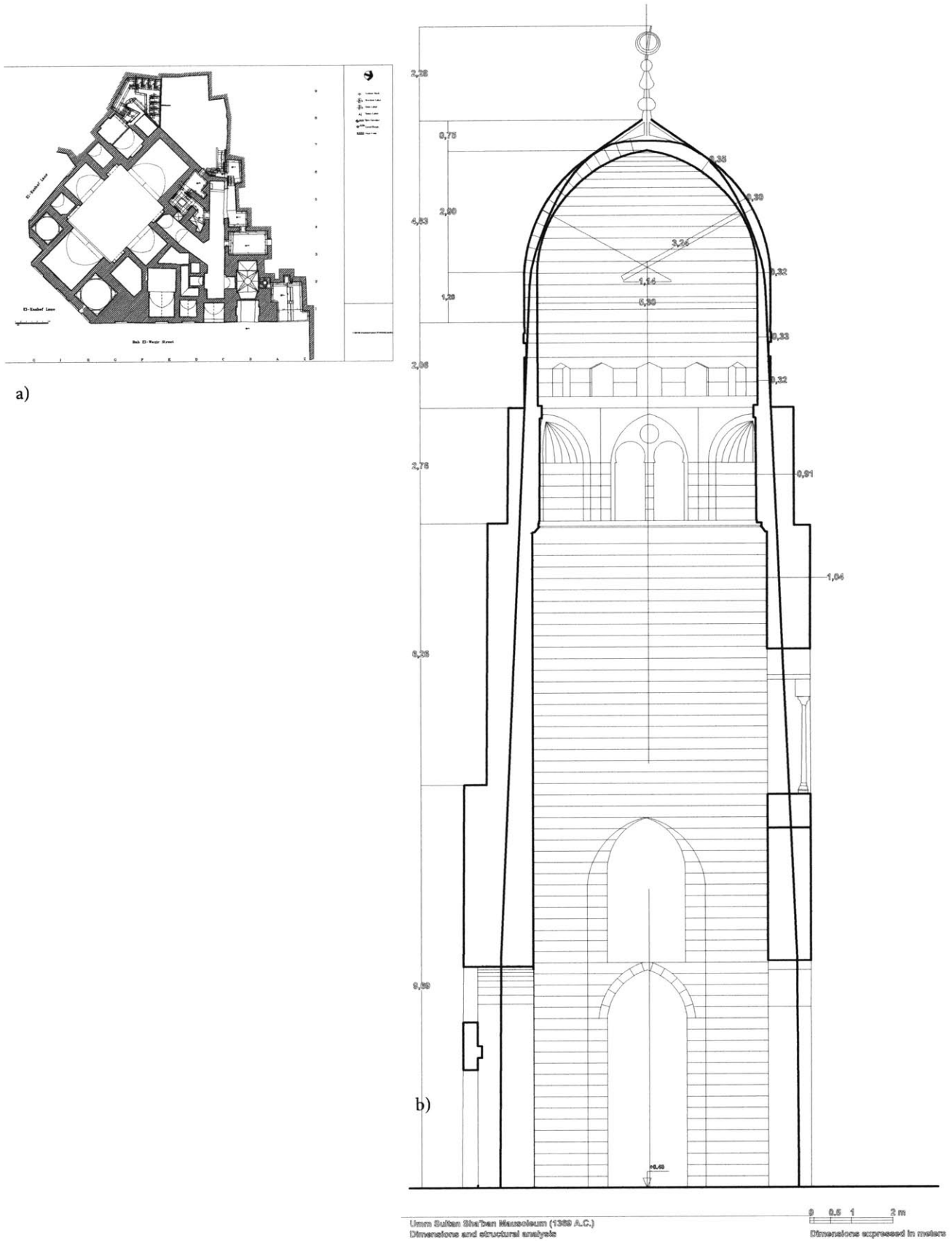
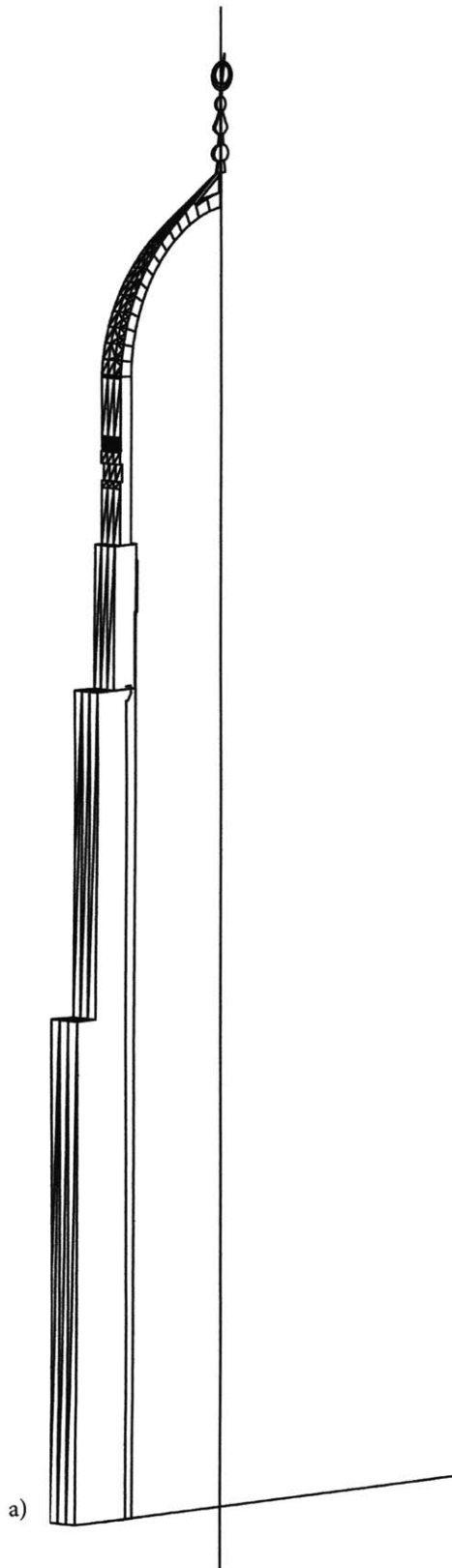
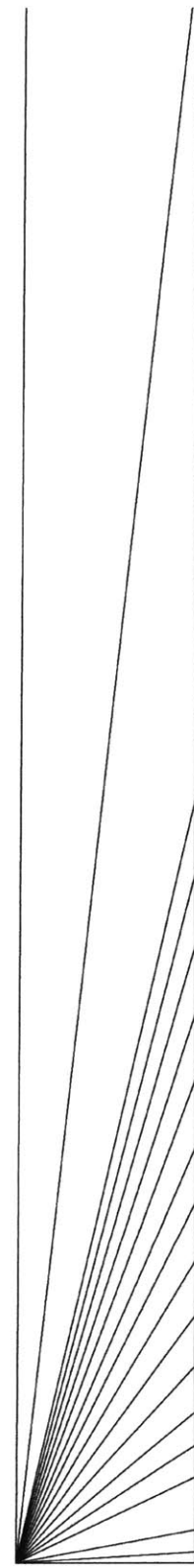


Fig. 2.7 a) Plan of the complex of Umm Sultan Sha'ban. b) Structural analysis of the Mausoleum. Within the section an hypothetical line of thrust has been traced at the limit of its fitting. Given the geometry of the dome, meridional stresses are not sufficient for the equilibrium and the contribution of hoop stresses is required. Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture



a)

b)



0 500 1000 2000N
1000N=101.871621 Kilograms force

Fig. 2. 8 Structural analysis of the Mausolem of Umm Sultan Sha'ban. The equilibrium is tested on a slice of 20 degree of the dome (a) .The funicular polygon for the construction of the line of thrust(b). Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture

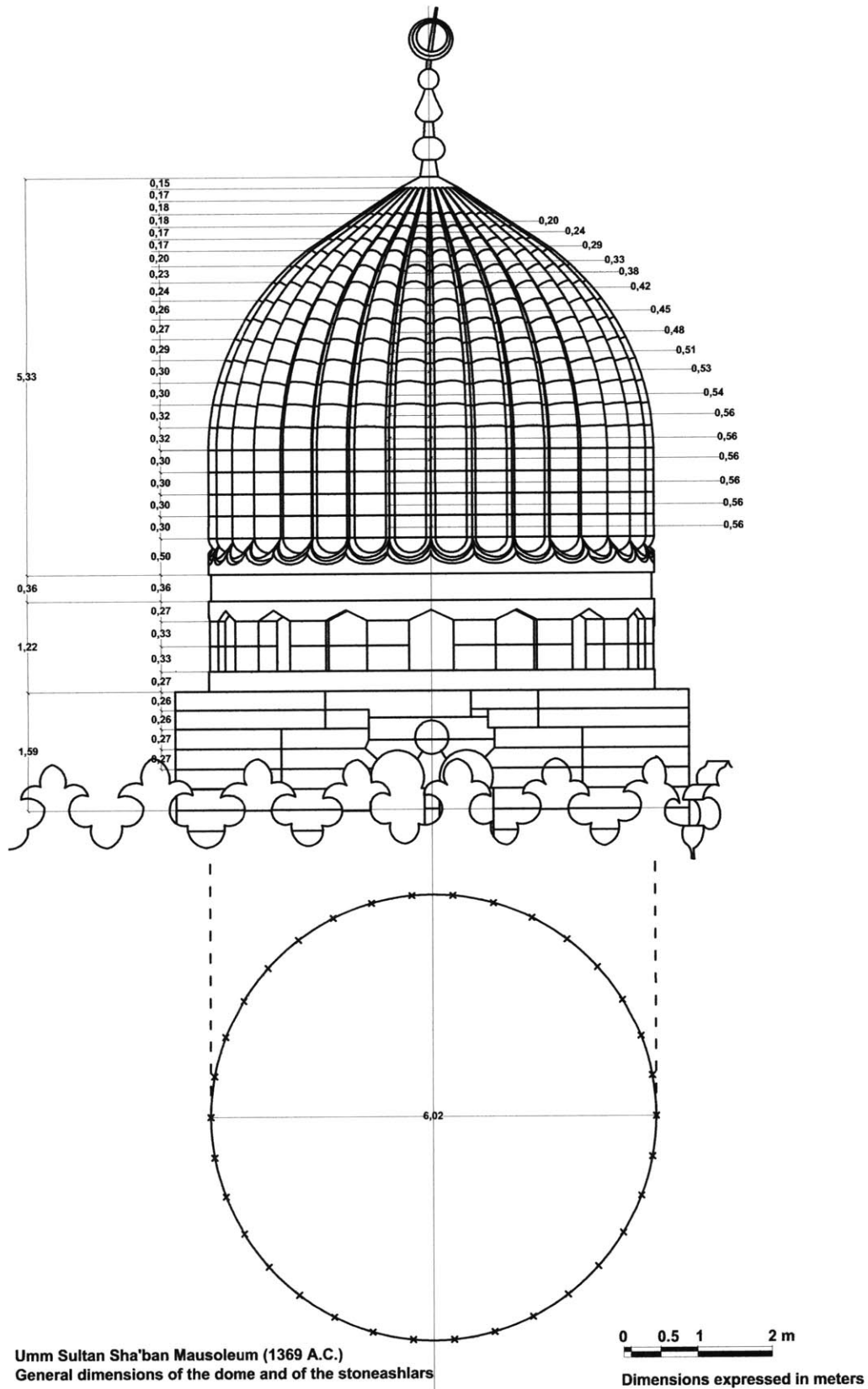


Fig. 2.9 Decoration pattern in the Mausoleum of Umm Sultan Sha'ban.
Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture

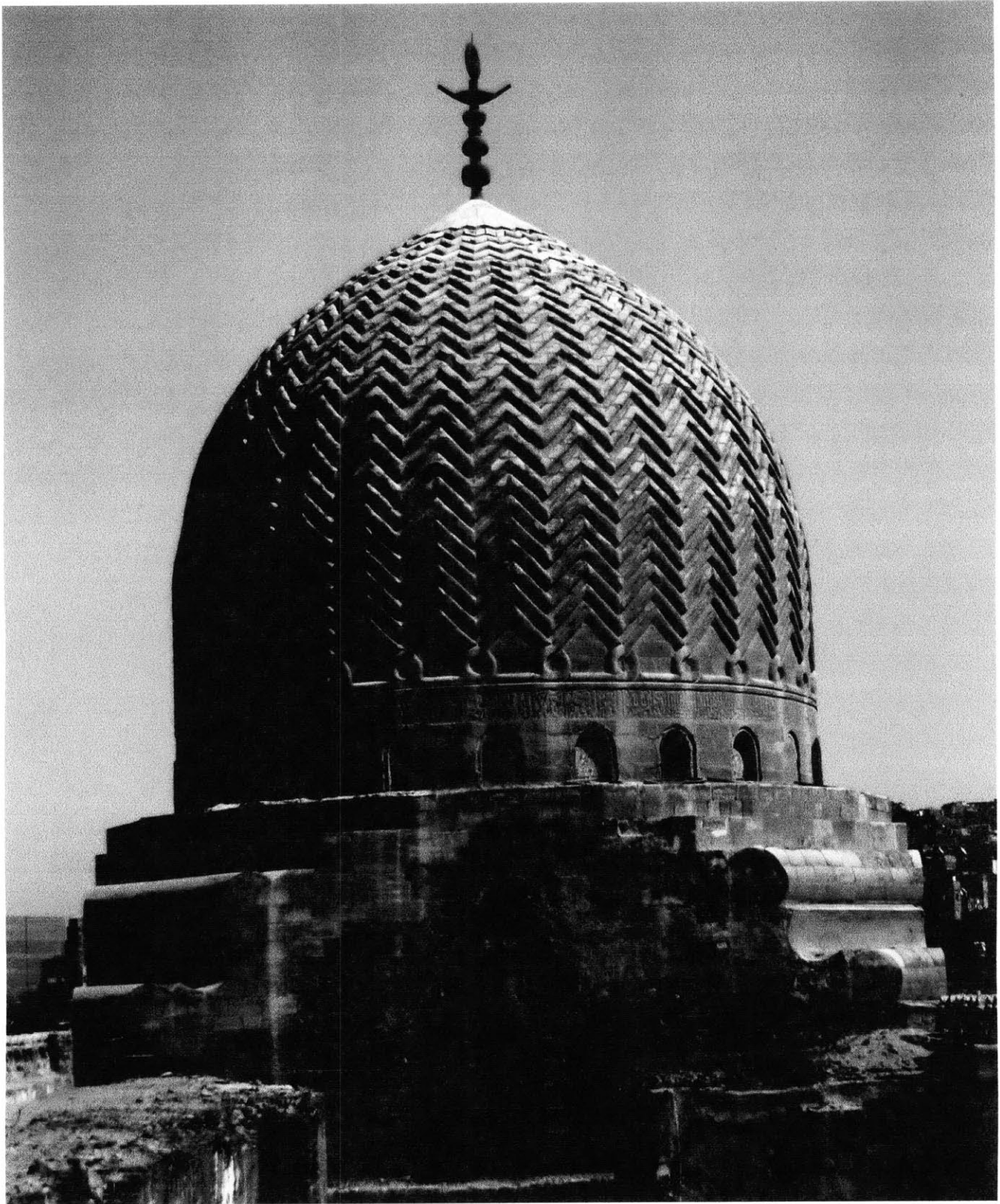


Fig. 2.10
Photo of Farag Ibn Barquq Mausoleum, North Eastern Dome

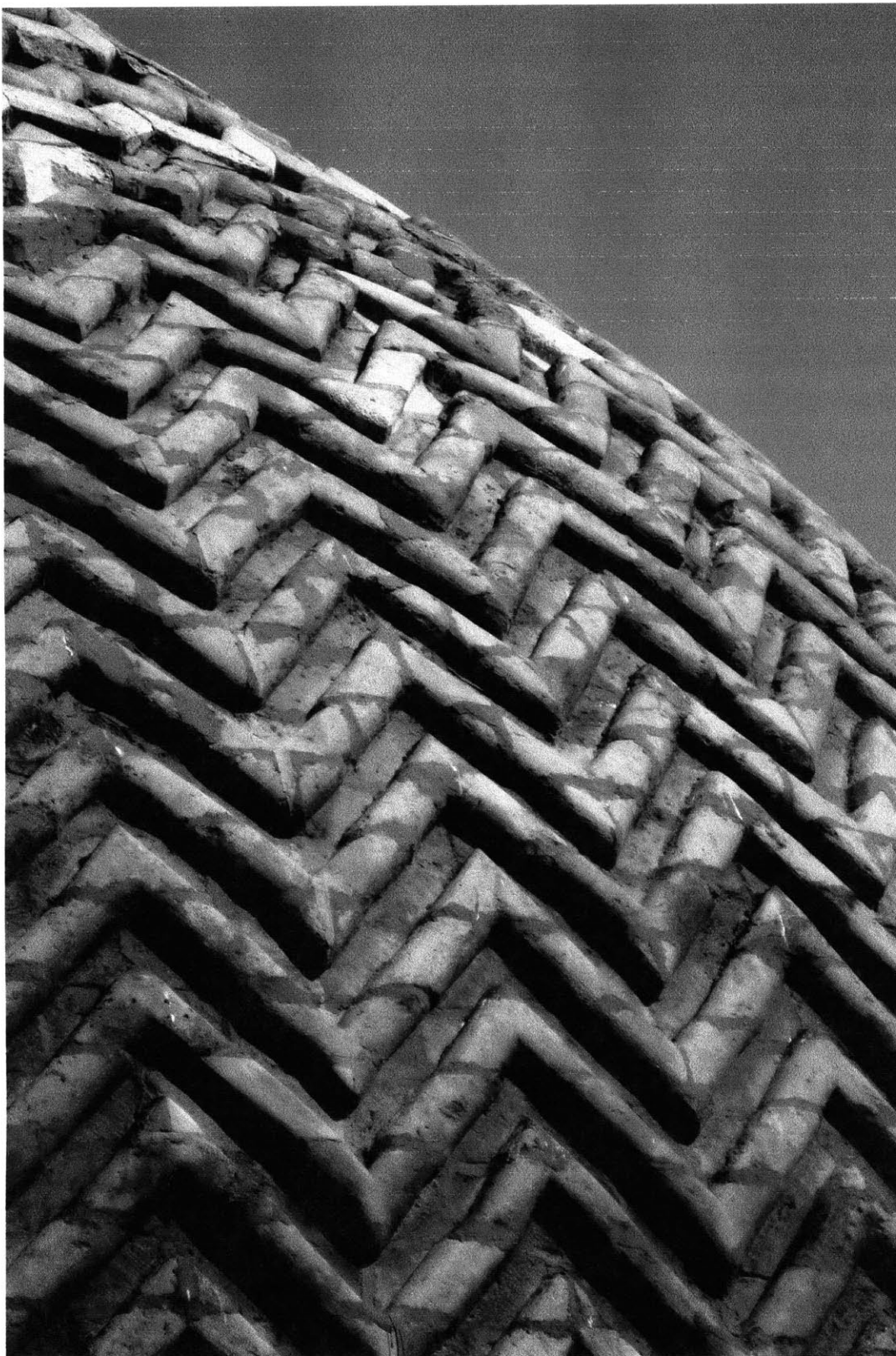


Fig. 2.11
Detail of the dome of Farag Ibn Barquq Mausoleum

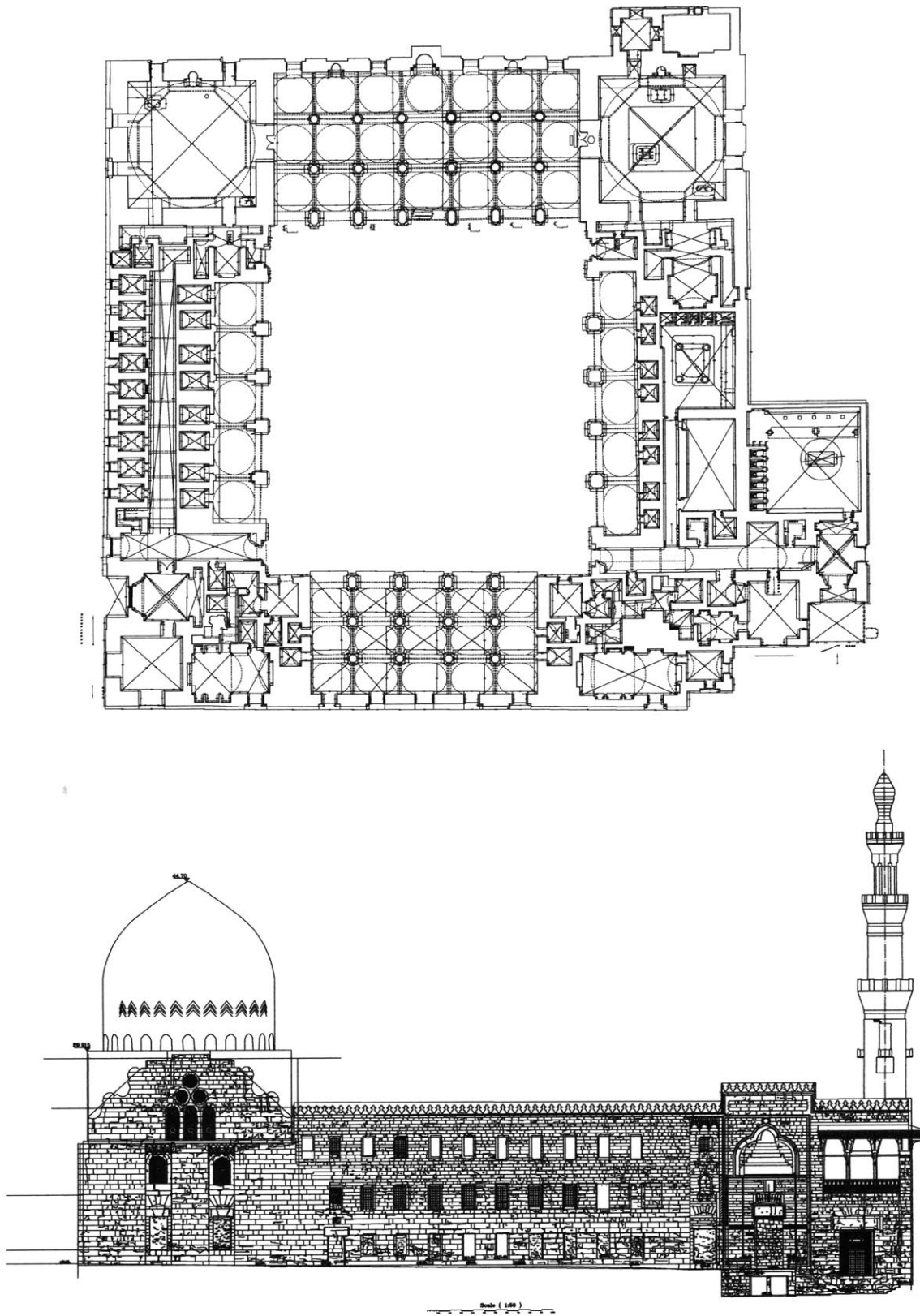


Fig. 2.12 Plan and facade of Farag Ibn Barquq Mausoleum
Drawing courtesy of The Arab Contractors, Osnam Ahmad Osnam & Co., Consulting Engineering & Technical Services

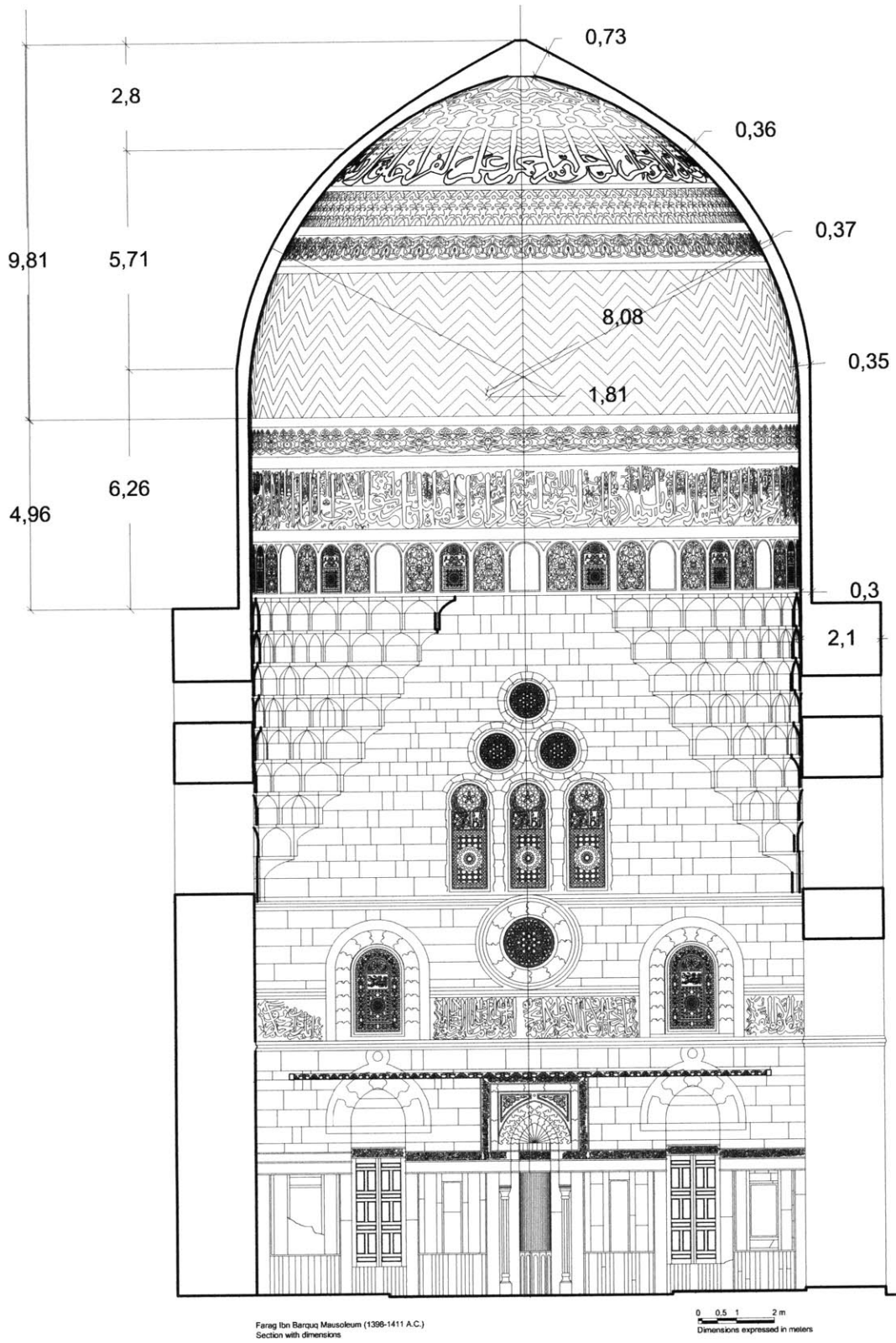
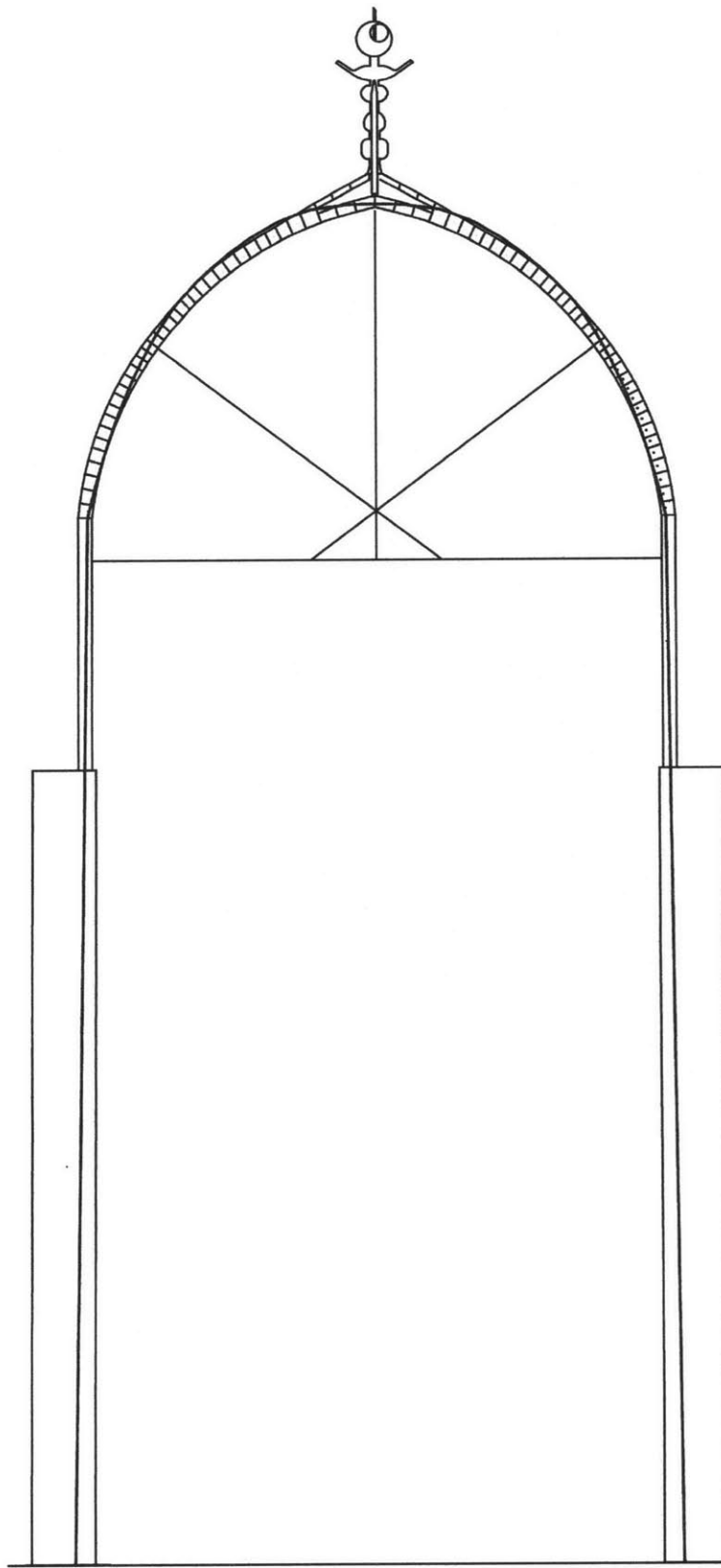


Fig. 2.13 Quoting of the general dymension of the Mausoleum of Farg Ibn Barquq
 Original drawing courtesy of The Arab Contractors, Osnam Ahmad Osnam & Co.,Consulting Engineering & Technical



Faraq Ibn Barqaz Mausoleum (1399-1411 A.C.)
Structural Analysis

0 0.5 1 2 m
Dimensions expressed in meters

Fig. 2.14

Section of the dome with the indication of the line of thrust within the section resulting from the structural analysis

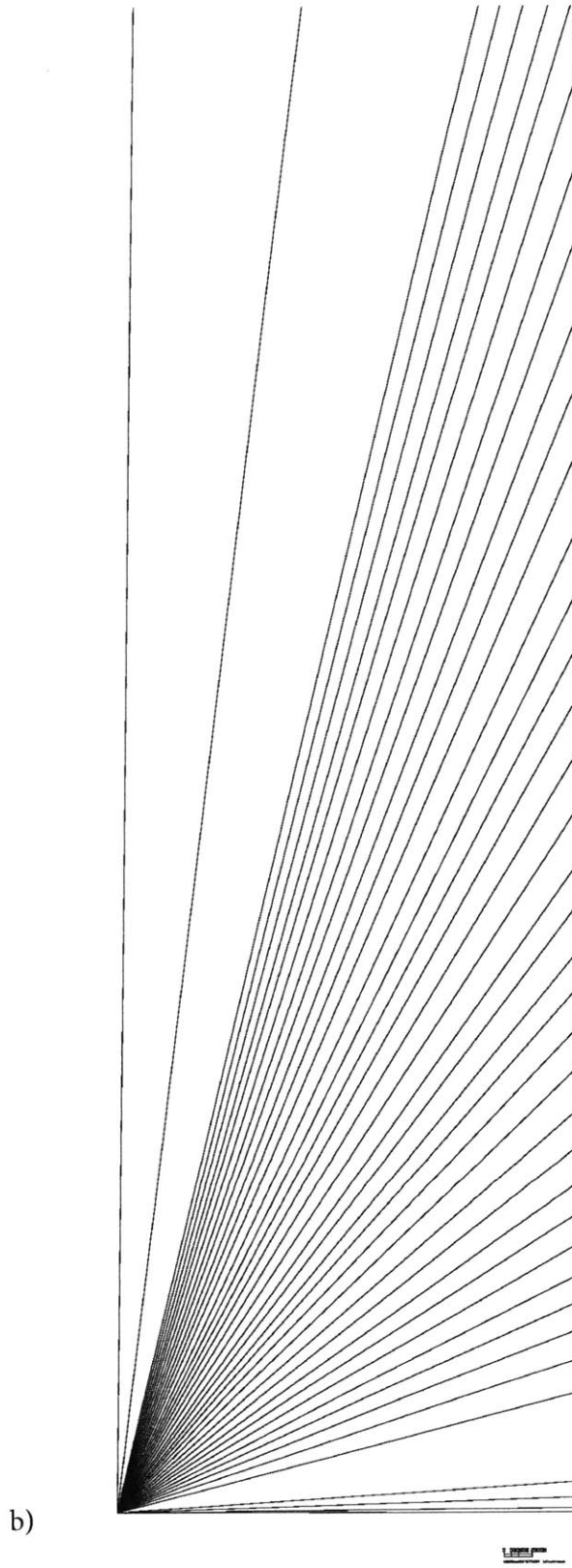
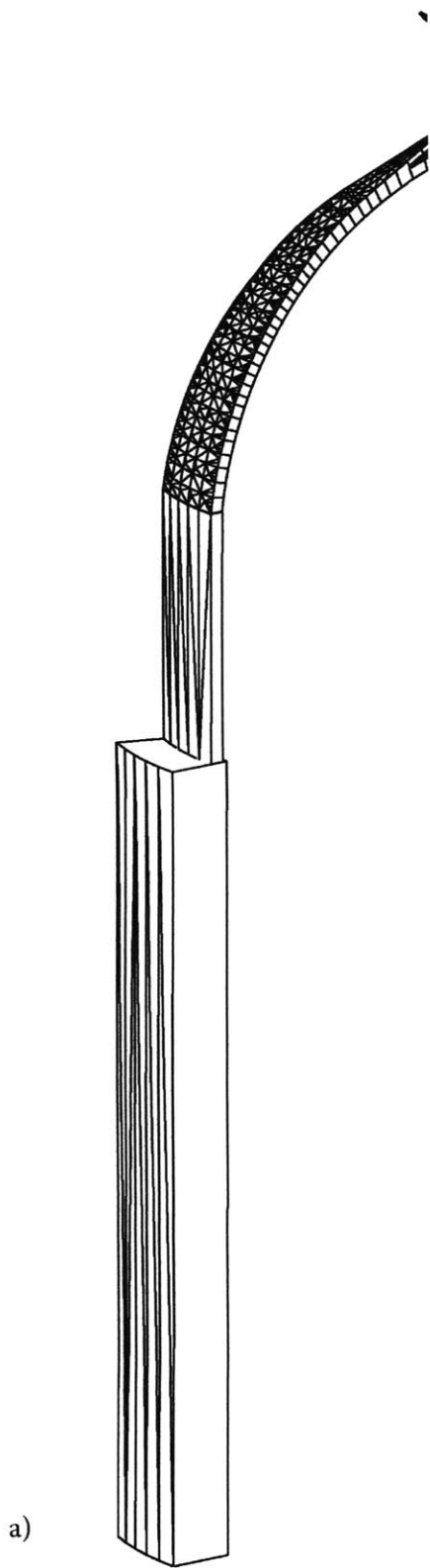


Fig. 2.15
Analysis of equilibrium for one slice of the dome (20 degree) a) and construction of the funicular polygon b)

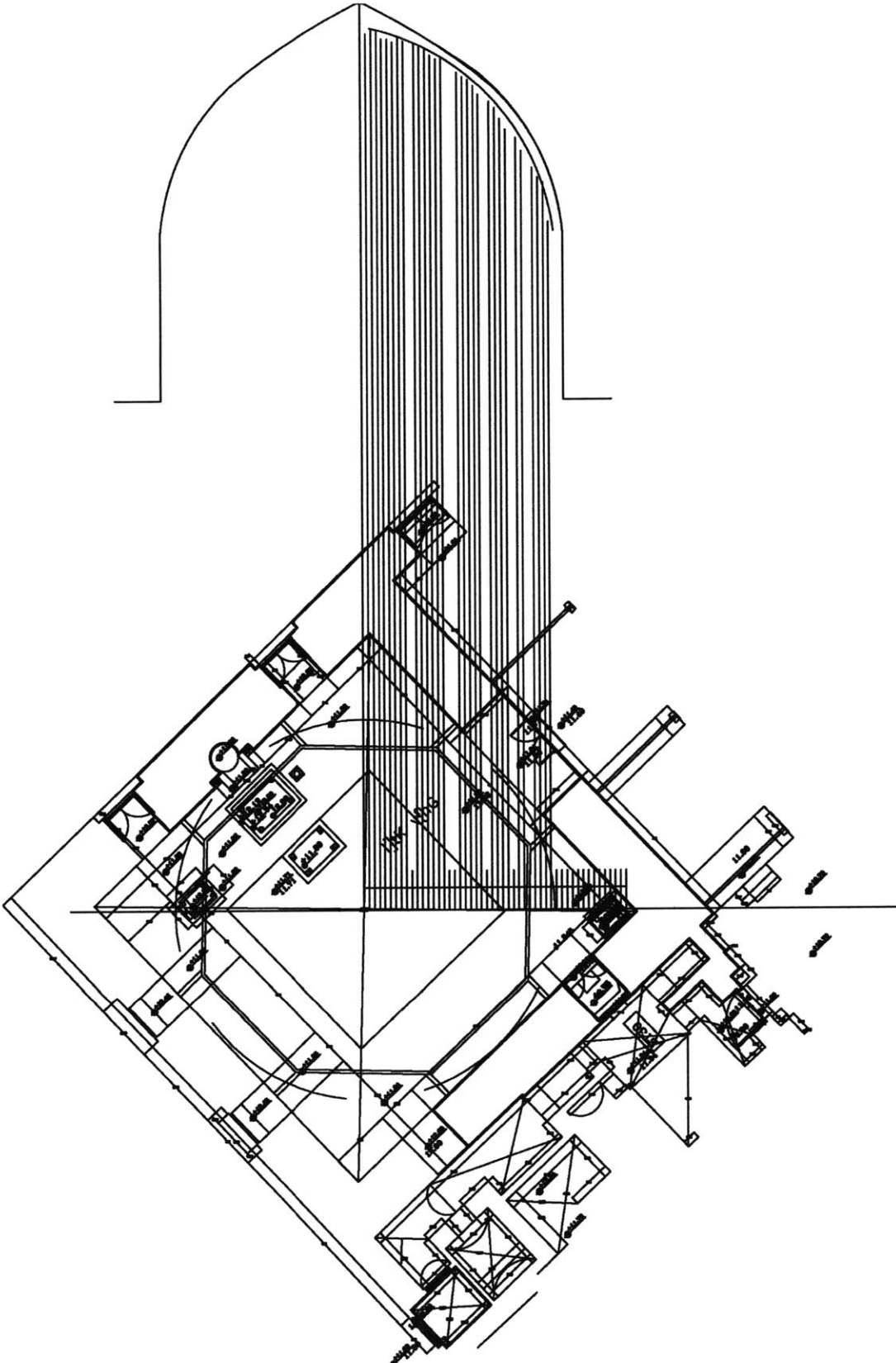


Fig. 2.16
Survey by the author with the laser disto to double check th eprofile of the dome

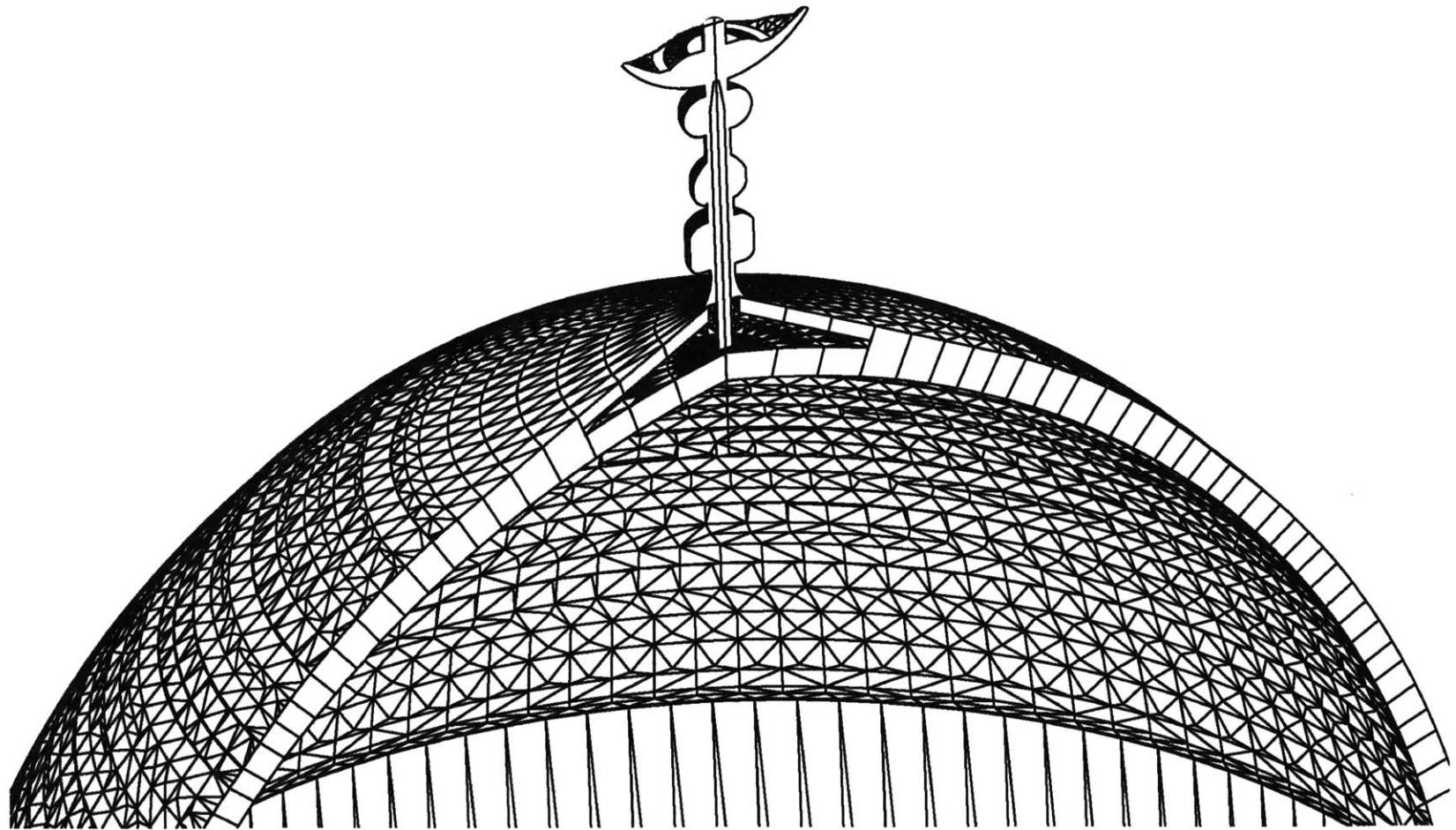


Fig. 2.17 Three dimensional reconstruction of
Drawing courtesy of The Arab Contractors, Osnam Ahmad Osnam & Co., Consulting Engineering & Technical Services

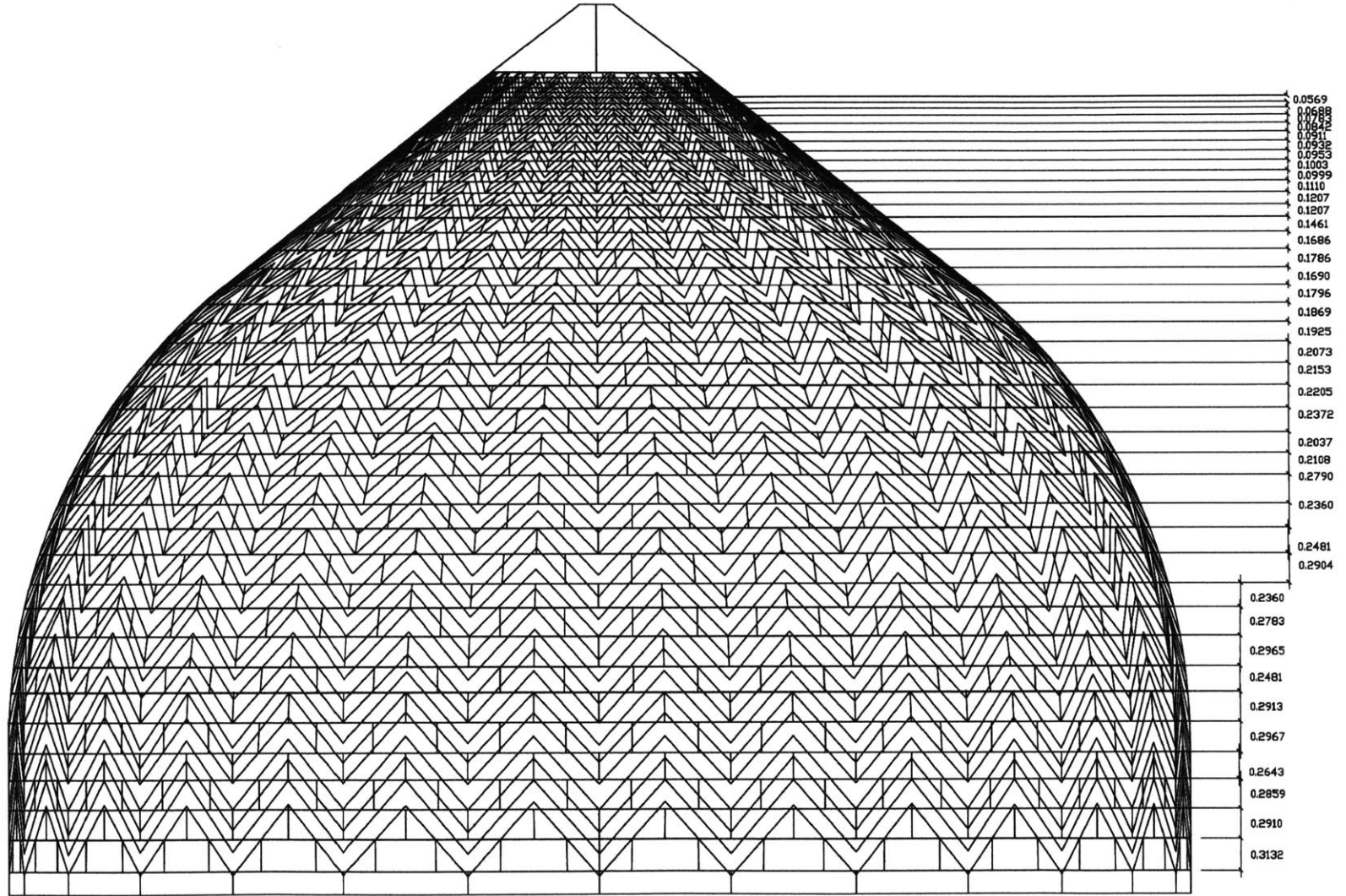


Fig. 2.18
Reconstruction of the decoration layout in the Mausoleum of Farag Ibn Barquq



Fig. 2.19 Funerary Complex of Amir Khayer Bek, 1502 A.D.



Fig. 2.20 Funerary Complex of Amir Khayer Bek, 1502 A.D., dome detail.

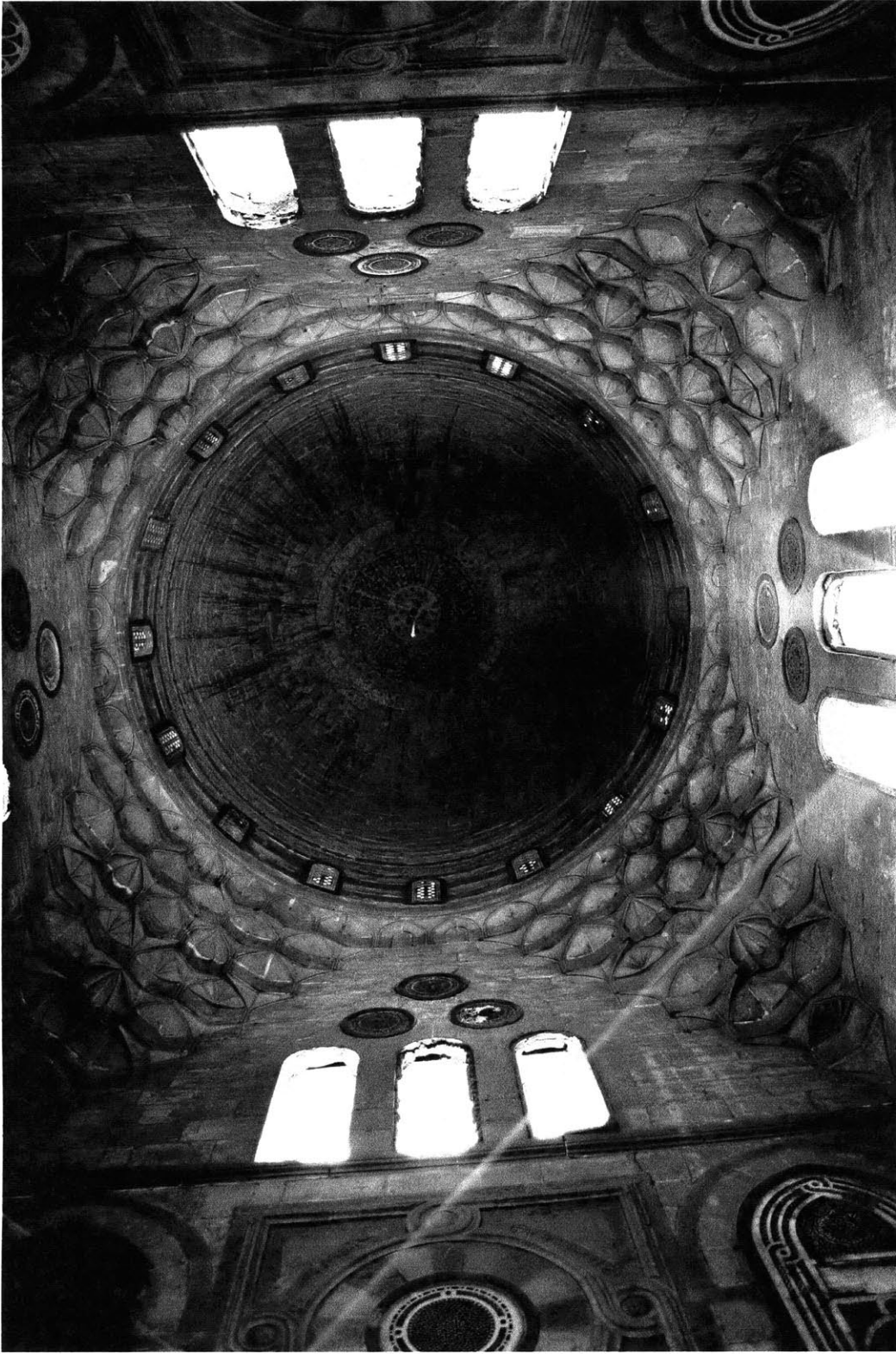


Fig 2.21
Interior view of the Mausoleum of Amir Khayer Bek, 1502 A.D.

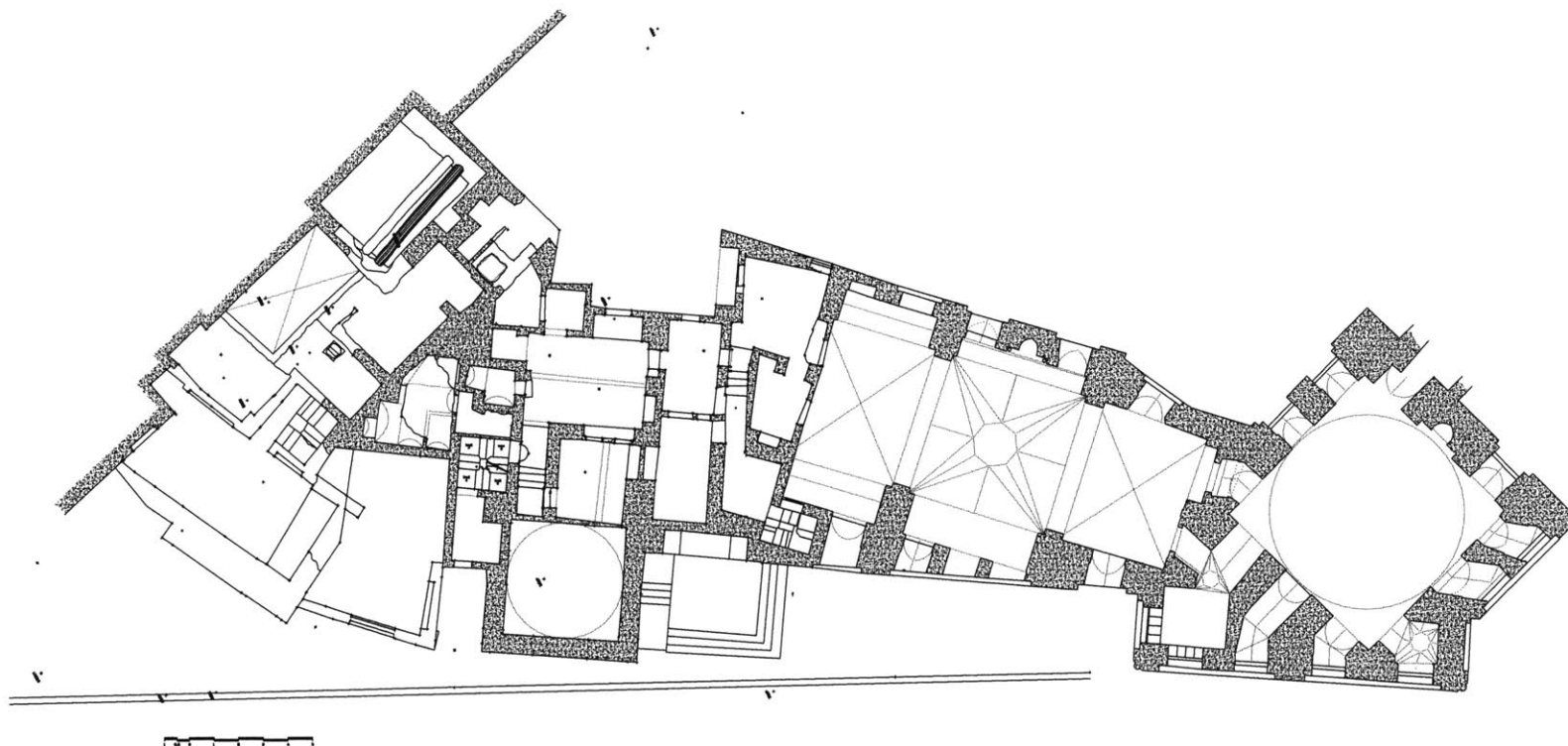
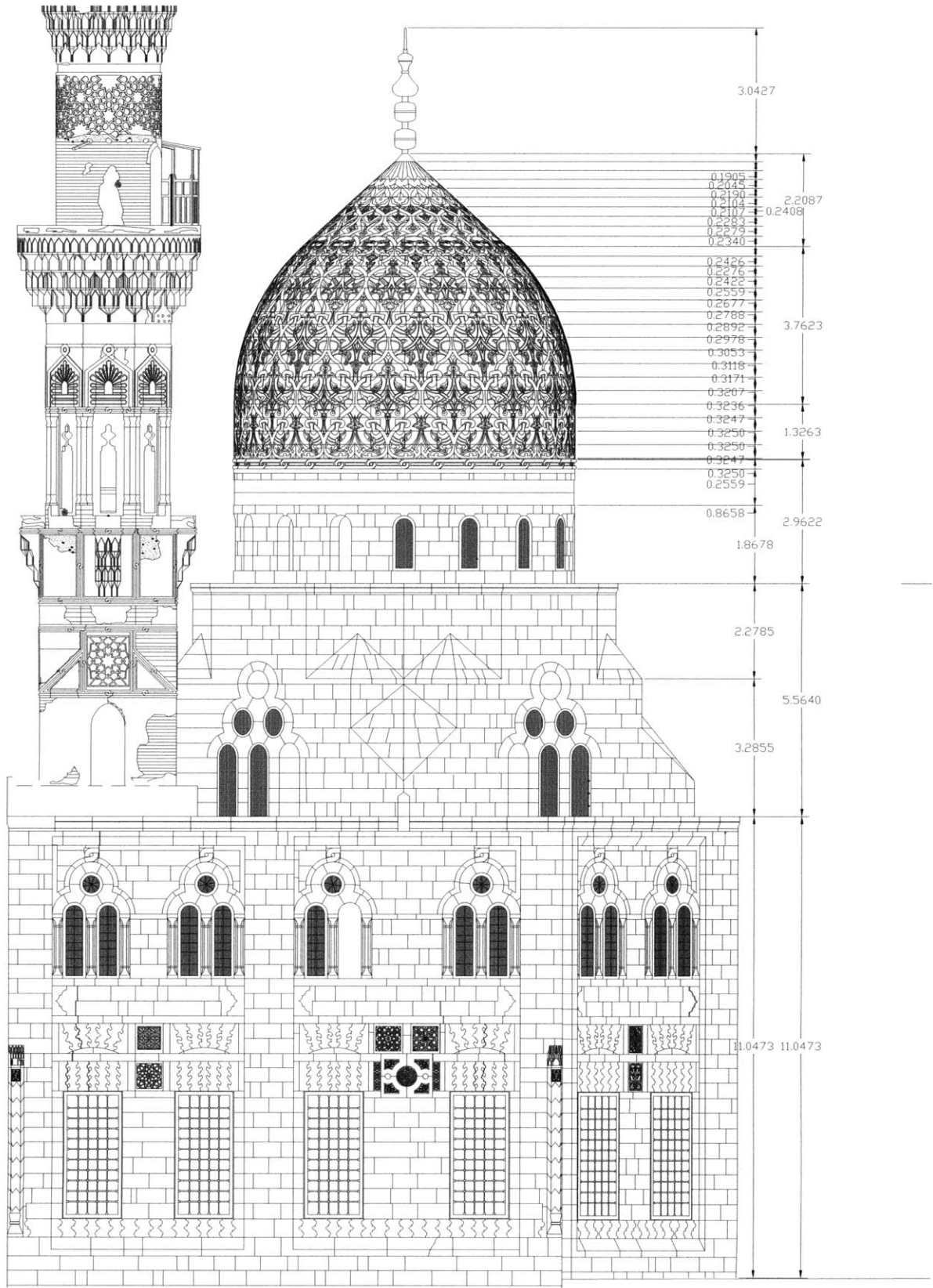


Fig. 2.22
Plan of Amir Khayer Bek Mausoleum
Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture



Amir Khayer Bek Mausoleum (1502 A.C.)

0 0.5 1 2 m

Fig . 2.23

Original drawings used for quoting are courtesy of the Aga Khan Trust for Culture

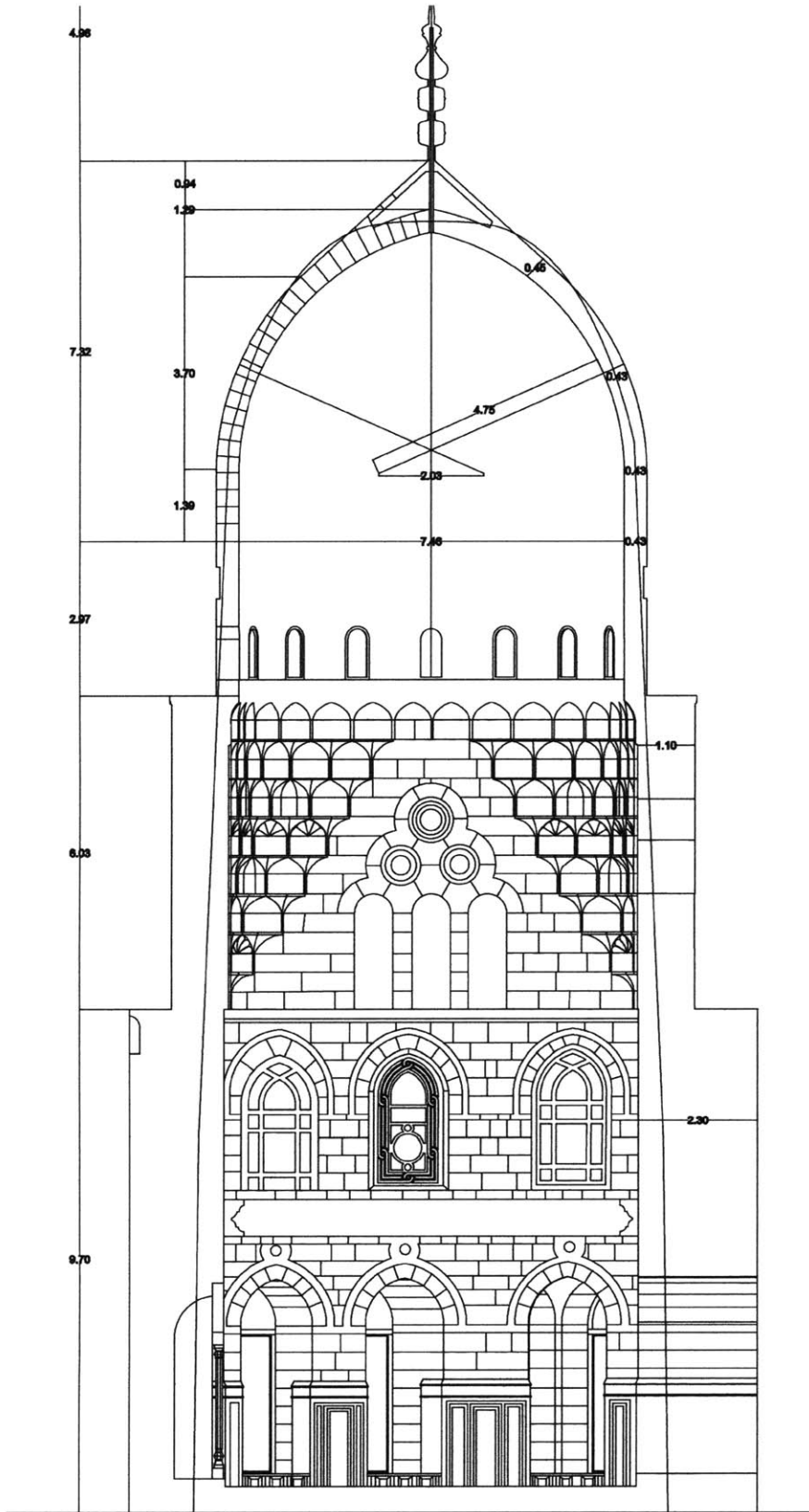


Fig. 2.24

Amir Khayer Bek Mausoleum (1502 A.C.)
Dimensions and Structural Analysis

0 0.5 1 2 m
Dimensions expressed in meters

Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture

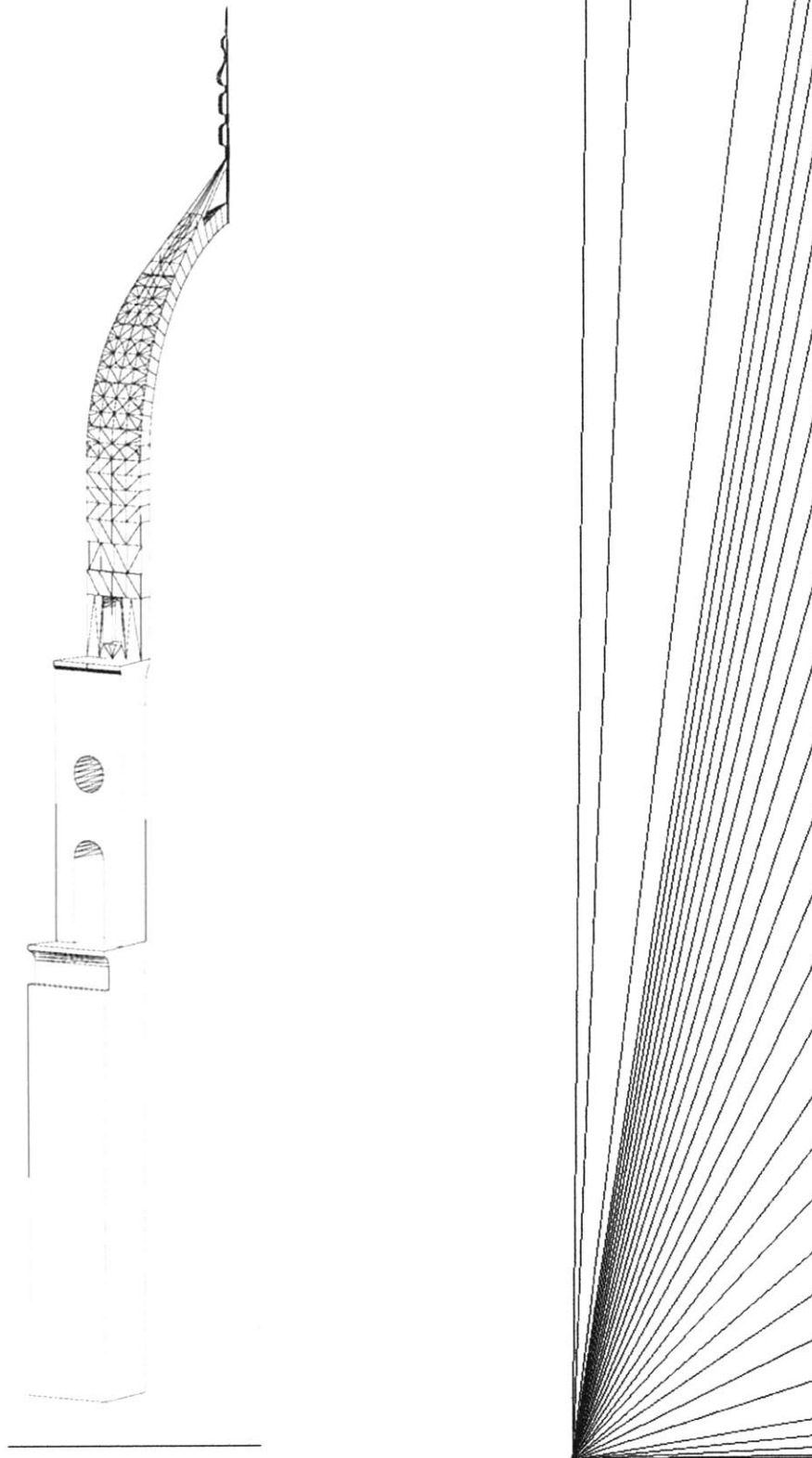


Fig.2.25
Slice of 20 degree of the dome of Kayer Bek Mausoleum used to test the
Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture

0 2000N

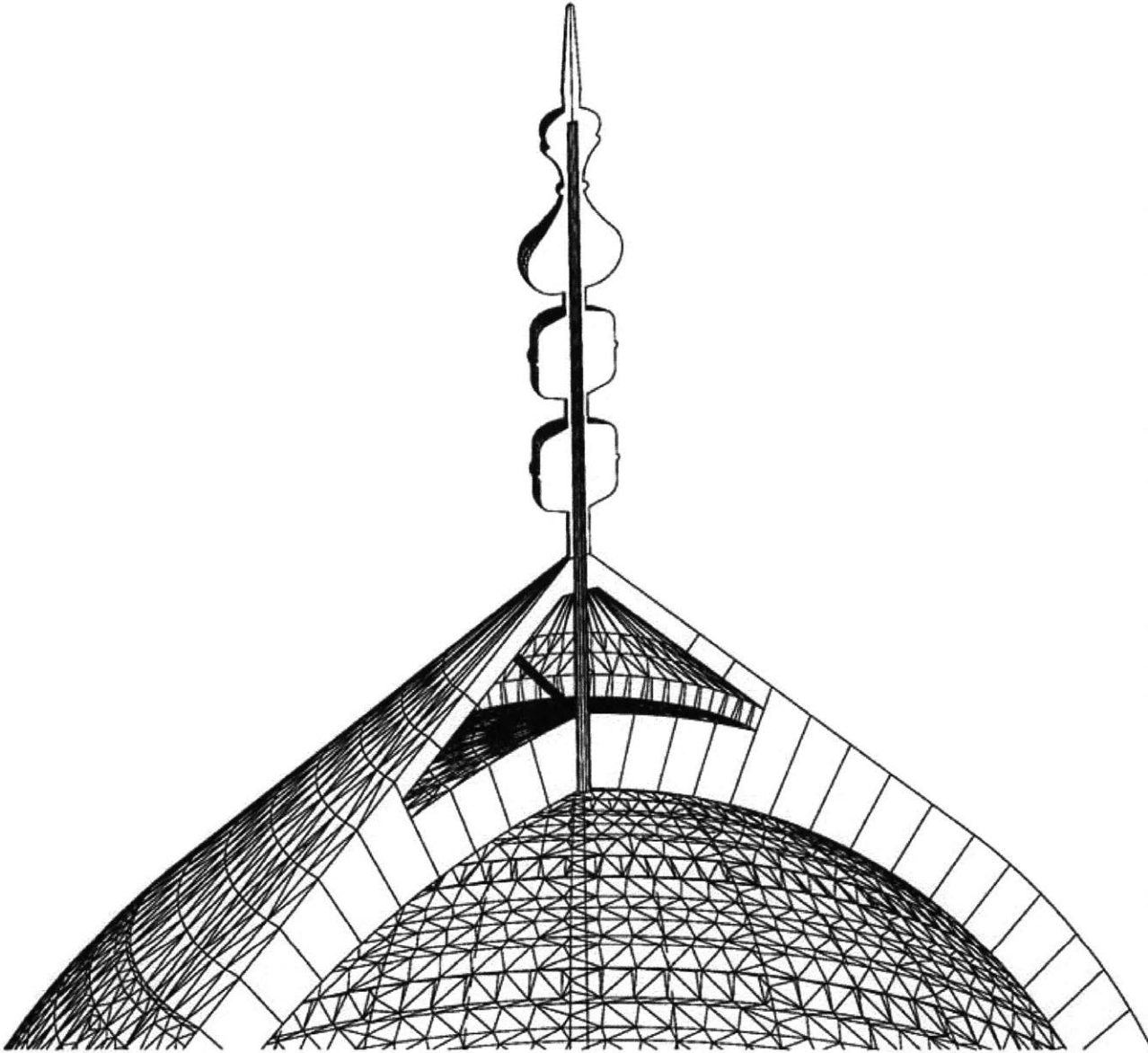


Fig. 2.26

Three dimensional reconstruction of the upper portion of Amir Khayer Bek Mausoleum by the author. Original drawings used for the analysis are courtesy of the Aga Khan Trust for Culture



Fig 2. 27 Detail of the doem decoration. The wood pegs used during construction are visible in correspondence of the joints.



Fig 2.28 Detail of the dome from the interior . Wood pegs used during construction are visible in correspondence of the joints.



a)



b)

Fig 2.29 a,b, The restoration of the upper part of Khayer Bek dome shows the stone blocks covering the hollow inside filled in with rubble. Pictures courtesy of the Aga Khan Trust for Culture.



Fig 2.30 This picture of the restoration works proves that at least the first four upper courses are constituted by two layers, the external one are stone blocks of 15-20 cm of thickness. Picture courtesy of the Aga Khan Trust for Culture.

Chapter 3 (Images)
**Observations and findings on
Cairene Mamluk Mausolea**

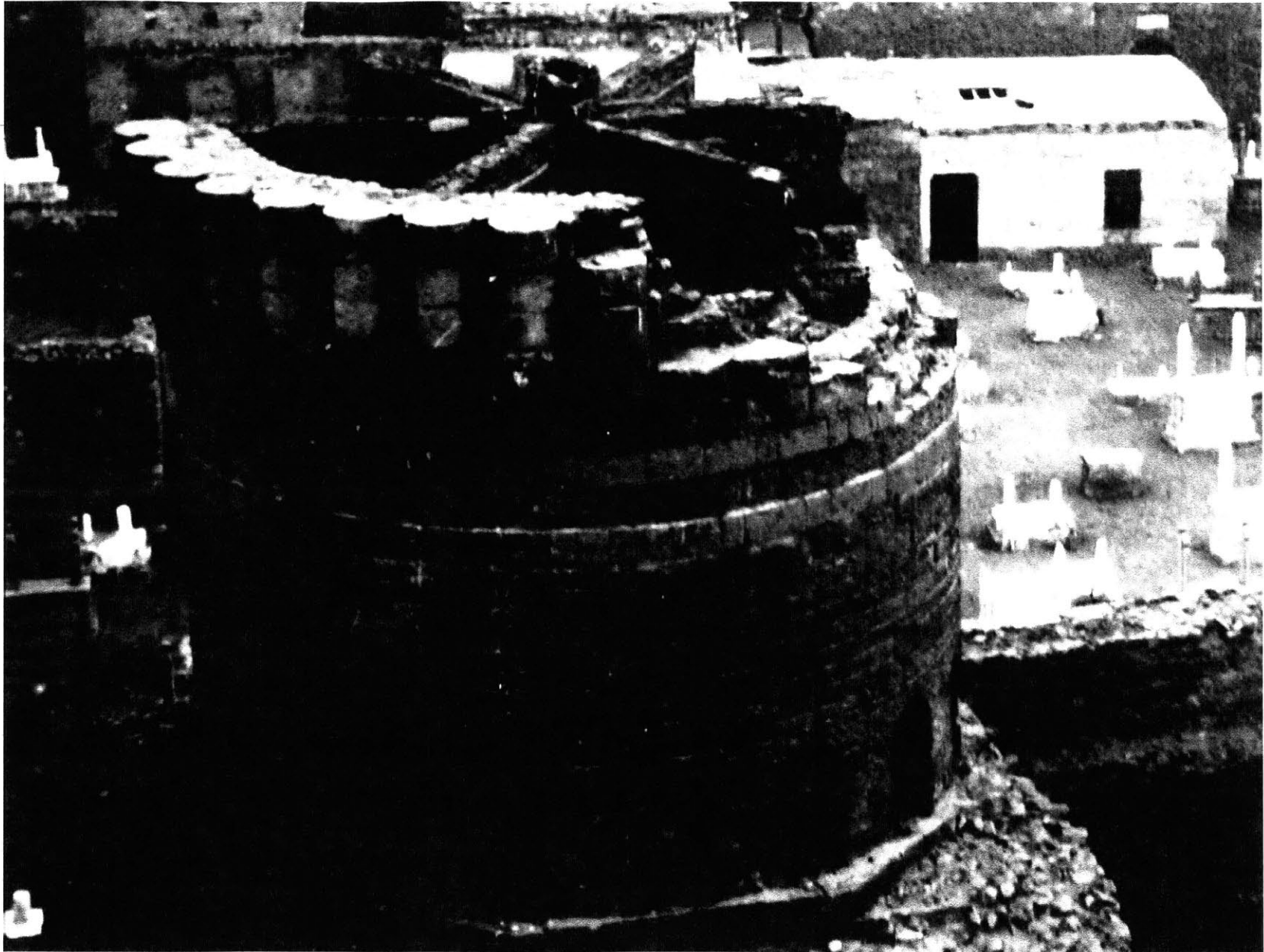


Fig 3.1
Detail of a broken dome showing a layer of brick behind the stone structure
Al-Sultaniyya Mausoleum 1350s-1360s A.D.

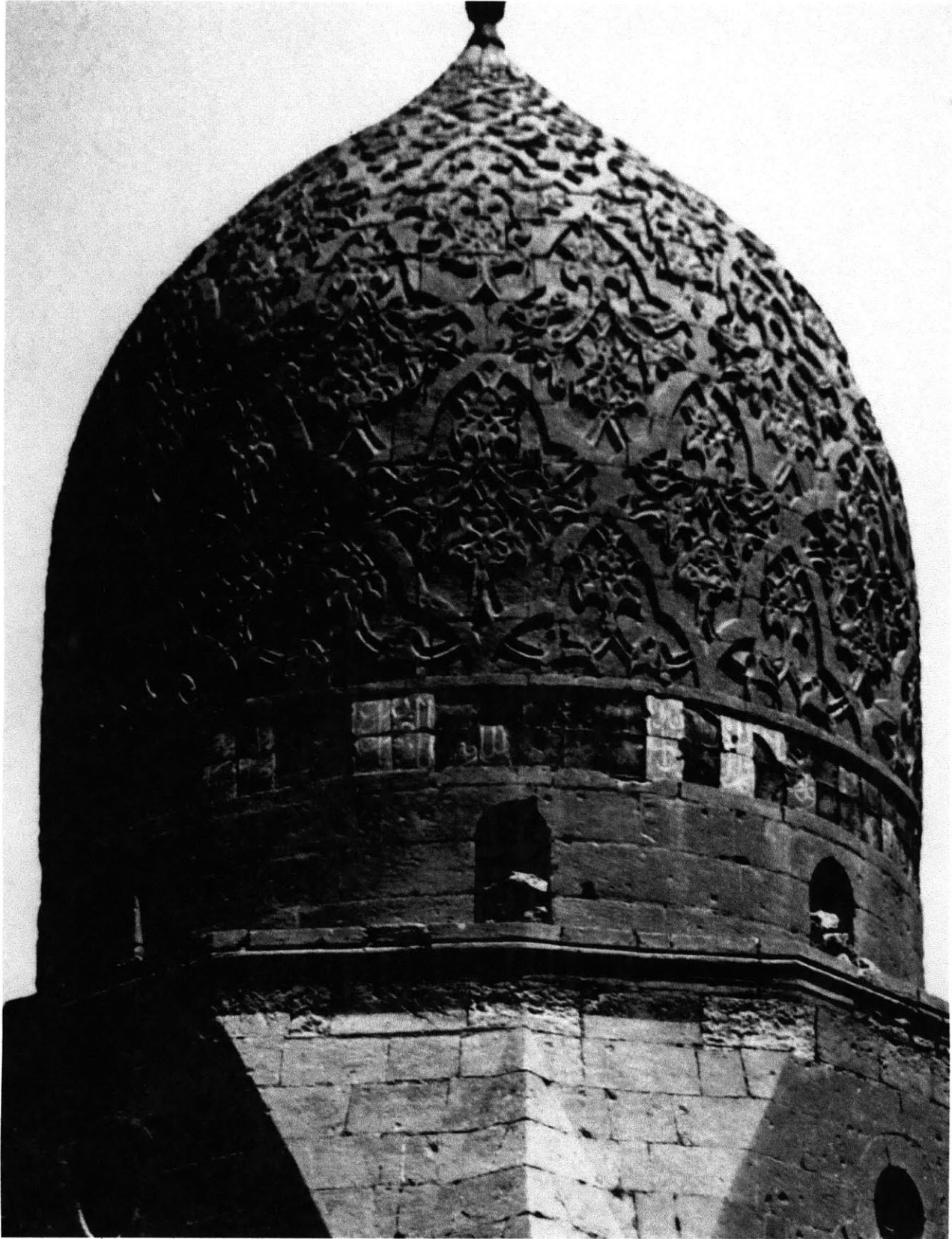


Fig 3.2
Detail a broken section of the drum showing thow the tiles holding the Coranic script have fallen 99
Barsbay al-Bajasi Mausoleum 1456 A.C.

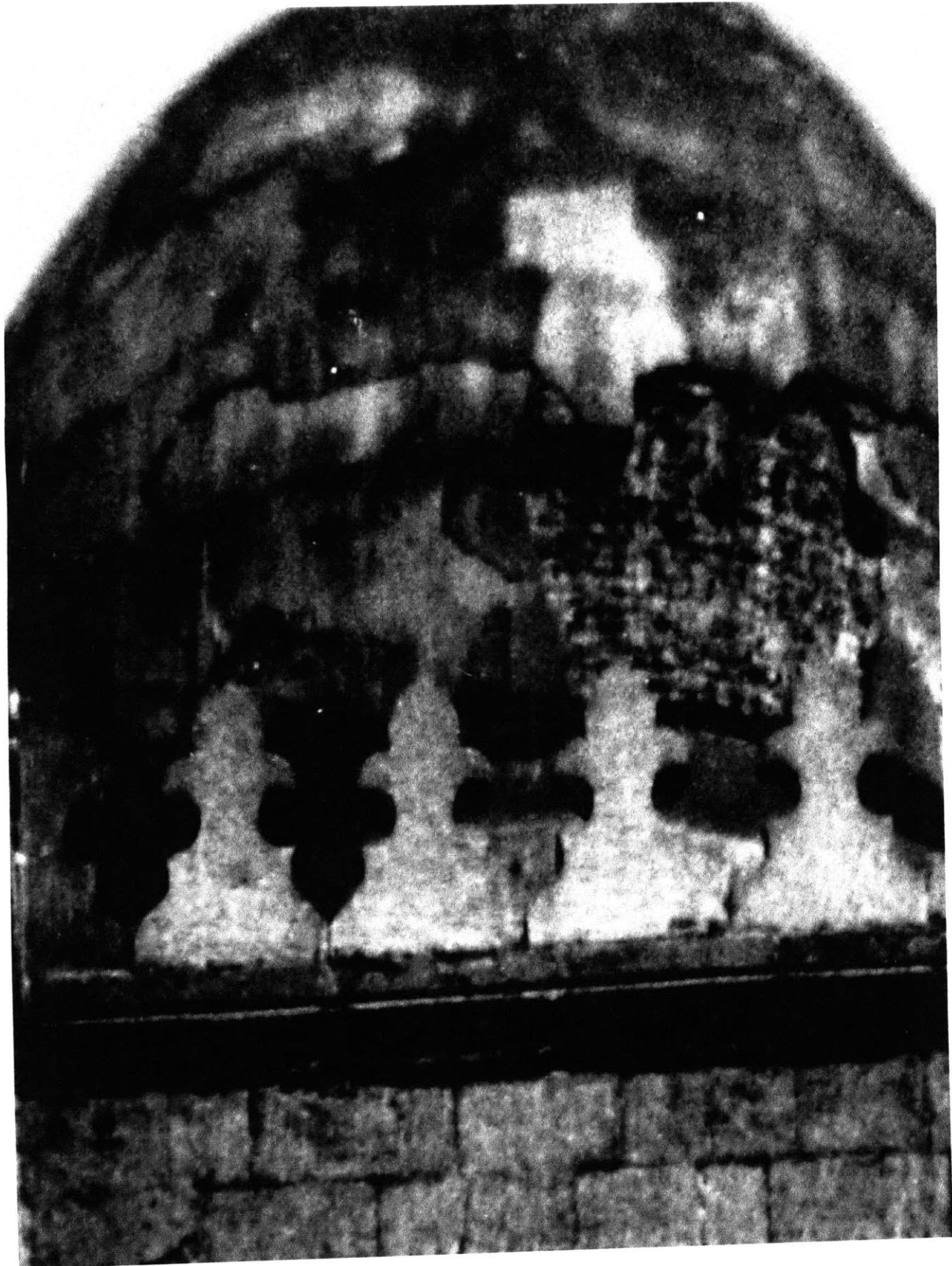


Fig 3.3
Detail of a broken dome showing a layer of brick behind the stone structure that have been finally 100
plastered

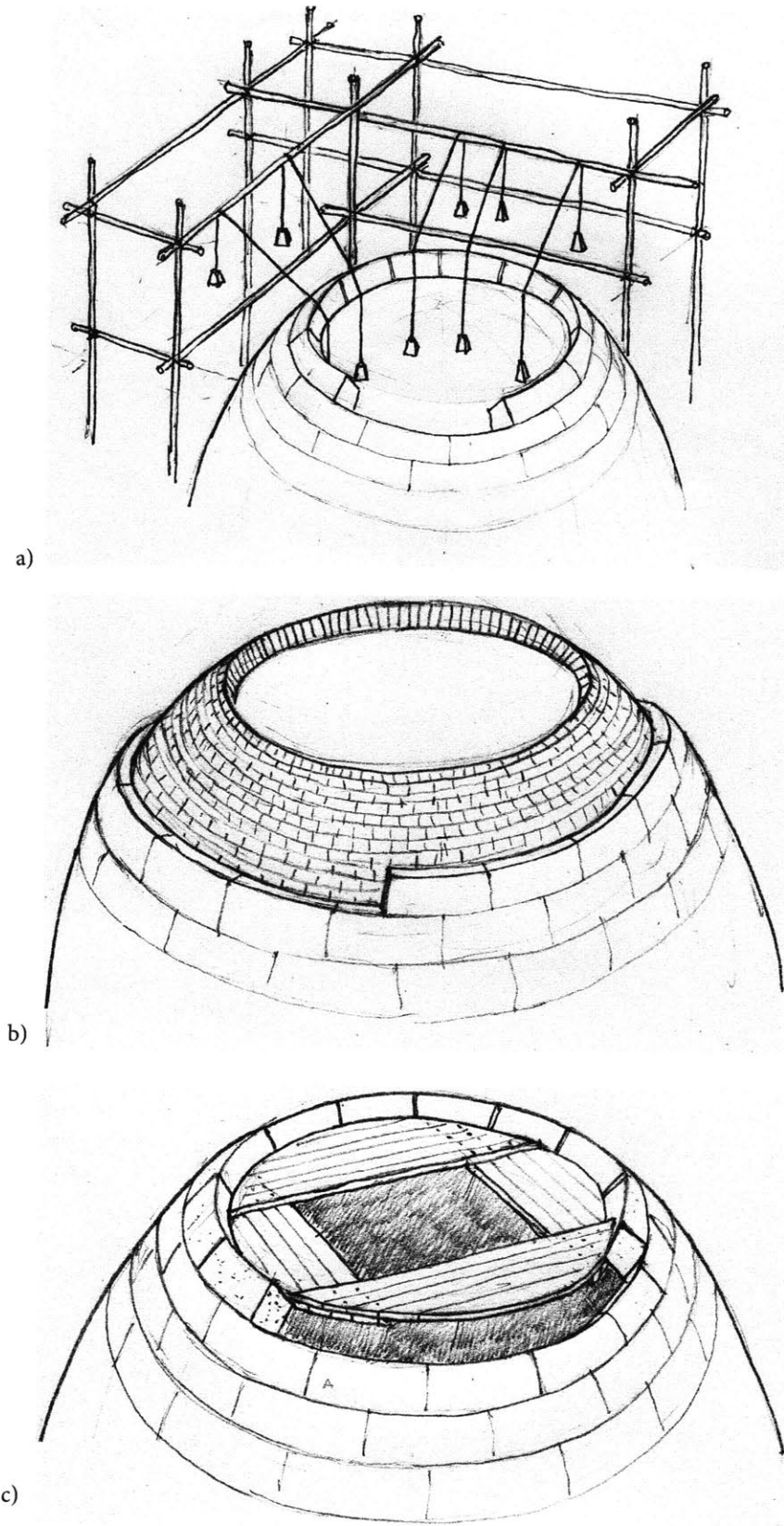


Fig 3.4 a,b,c
Reconstruction by the author of three possible building processes for the dome

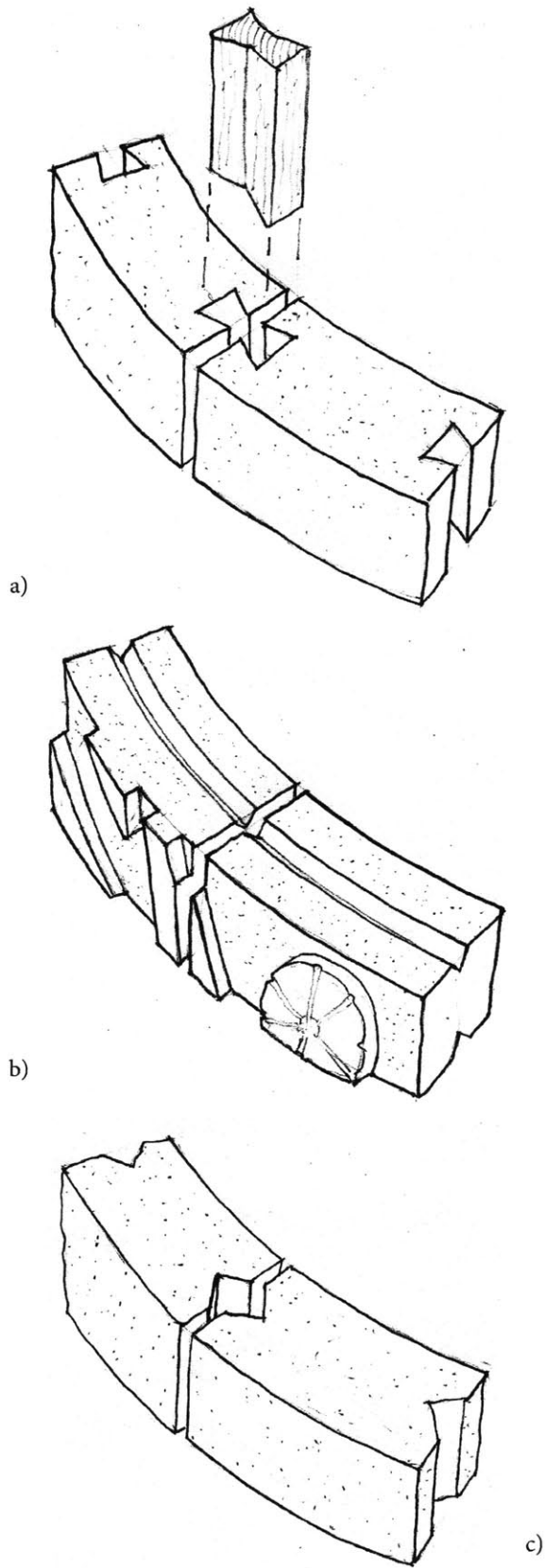


Fig 3.5
Reconstruction by the author of some of the solutions to hold the stone ashlars together

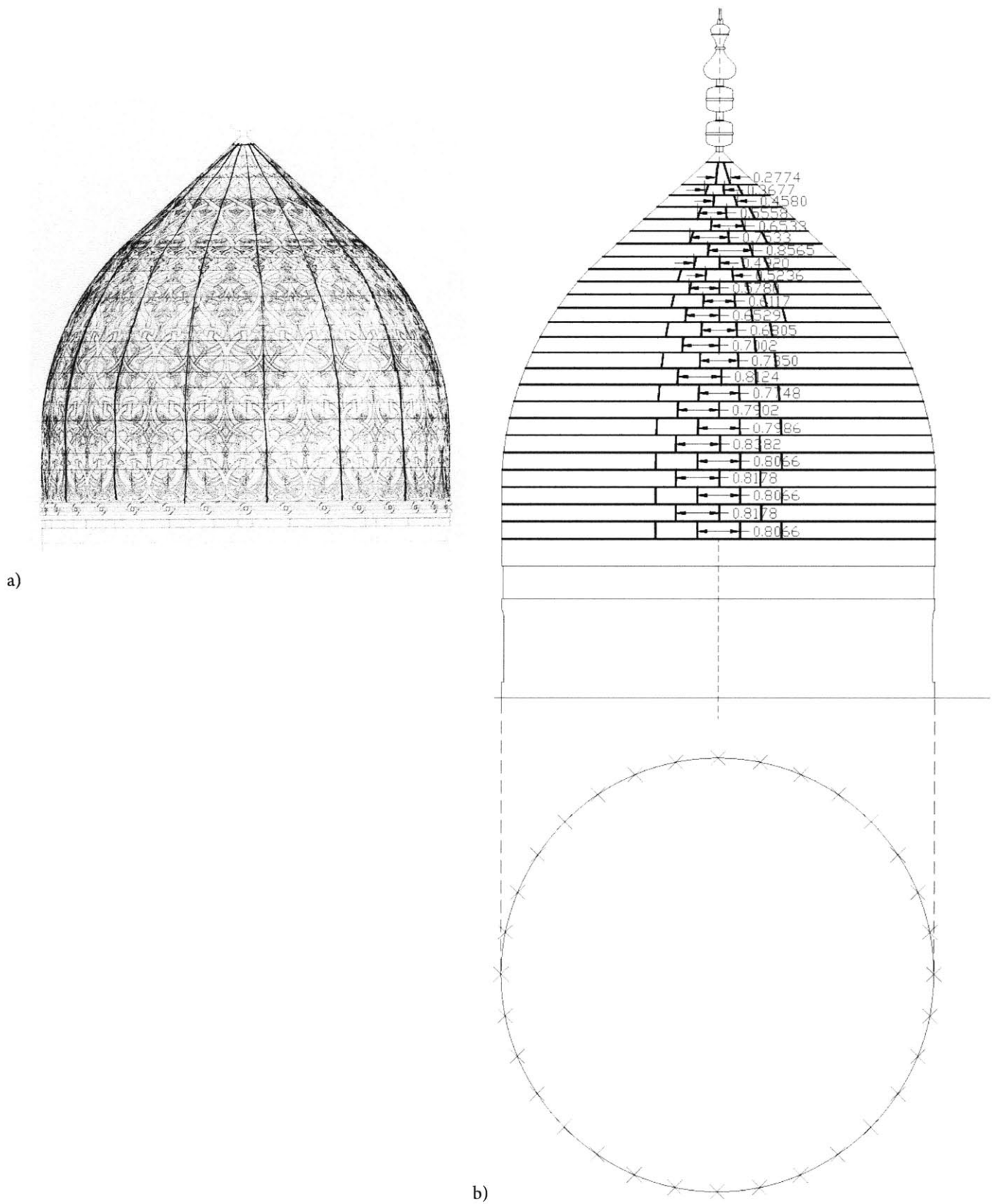


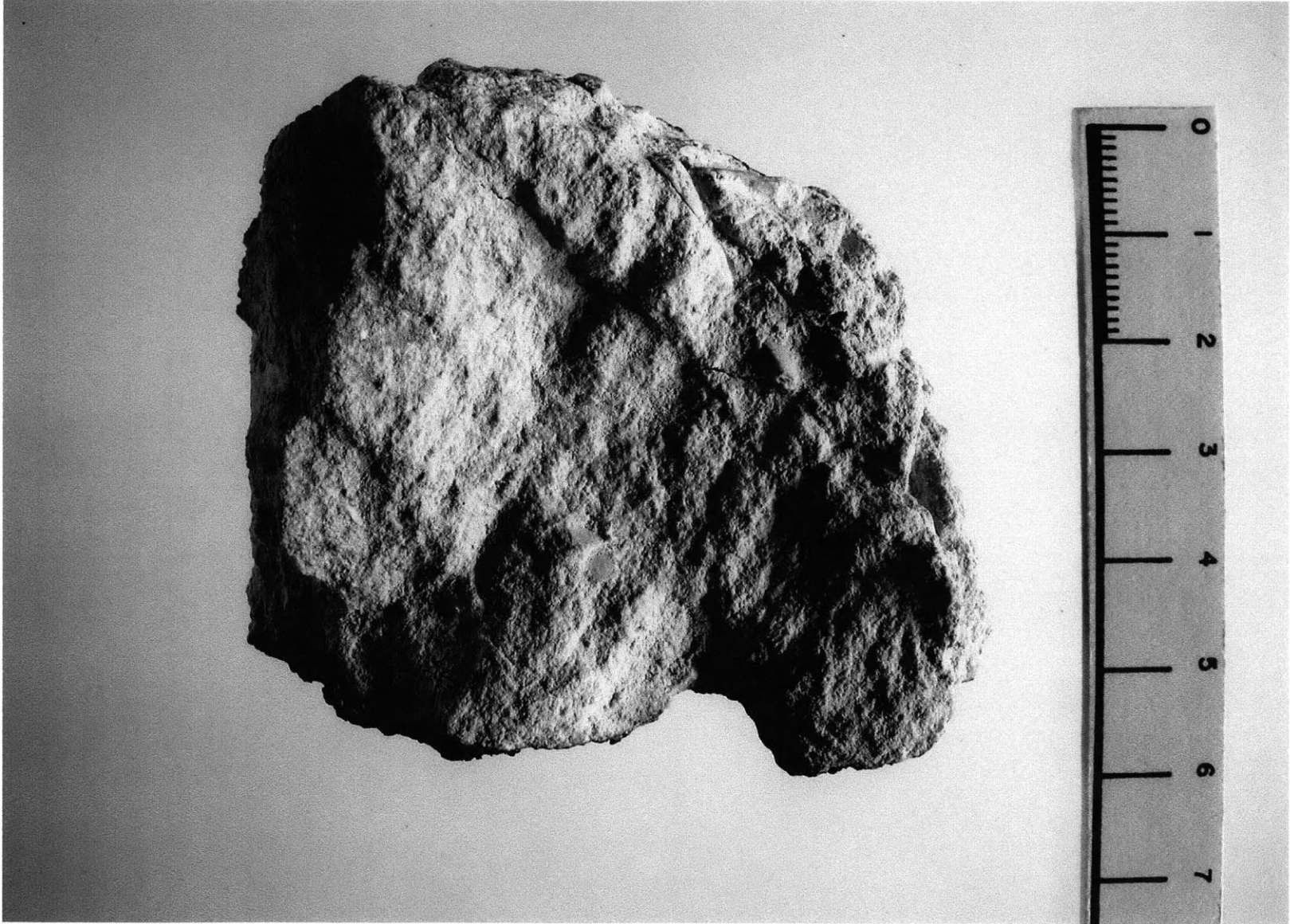
Fig 3.6

a) Decoration pattern based on the repetition of a slice of design for a number multiple of 4.
 b) Dimensions of a typical stone ashlar per ring in the Khayer Bek Mausoleum

Appendix
Laboratory sample analysis



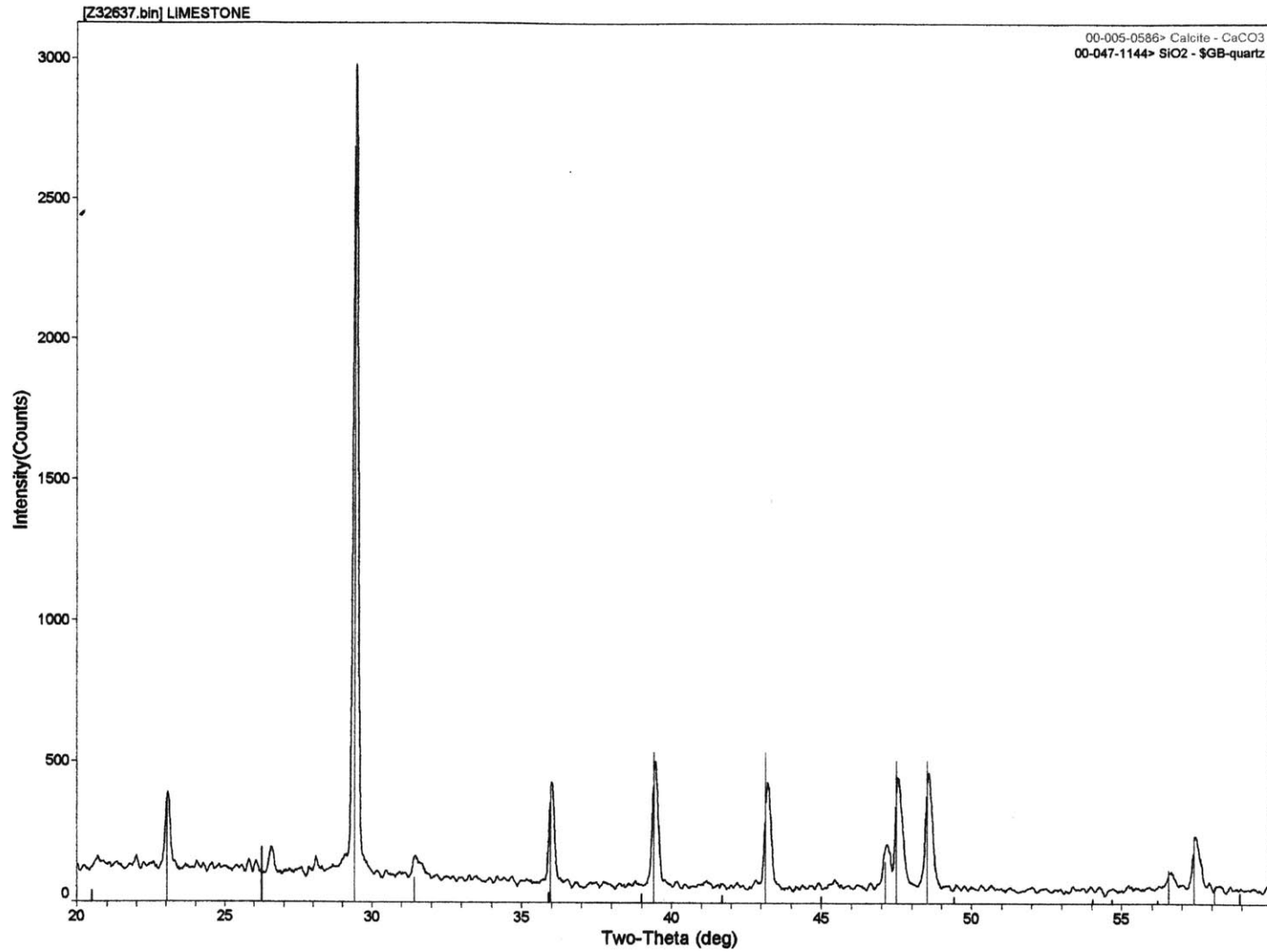
Sample from the upper course (external decoration) of Khayer Bek Dome analyzed in the laboratory of the MIT Department of Material Science by Professor Heather Lechtman and Elizabeth Hendrix



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Sample from the upper course (interior side) of Khayer Bek Dome analyzed in the laboratory of the MIT Department of Material Science by Professor Heather Lechtman and Elizabeth Hendrix

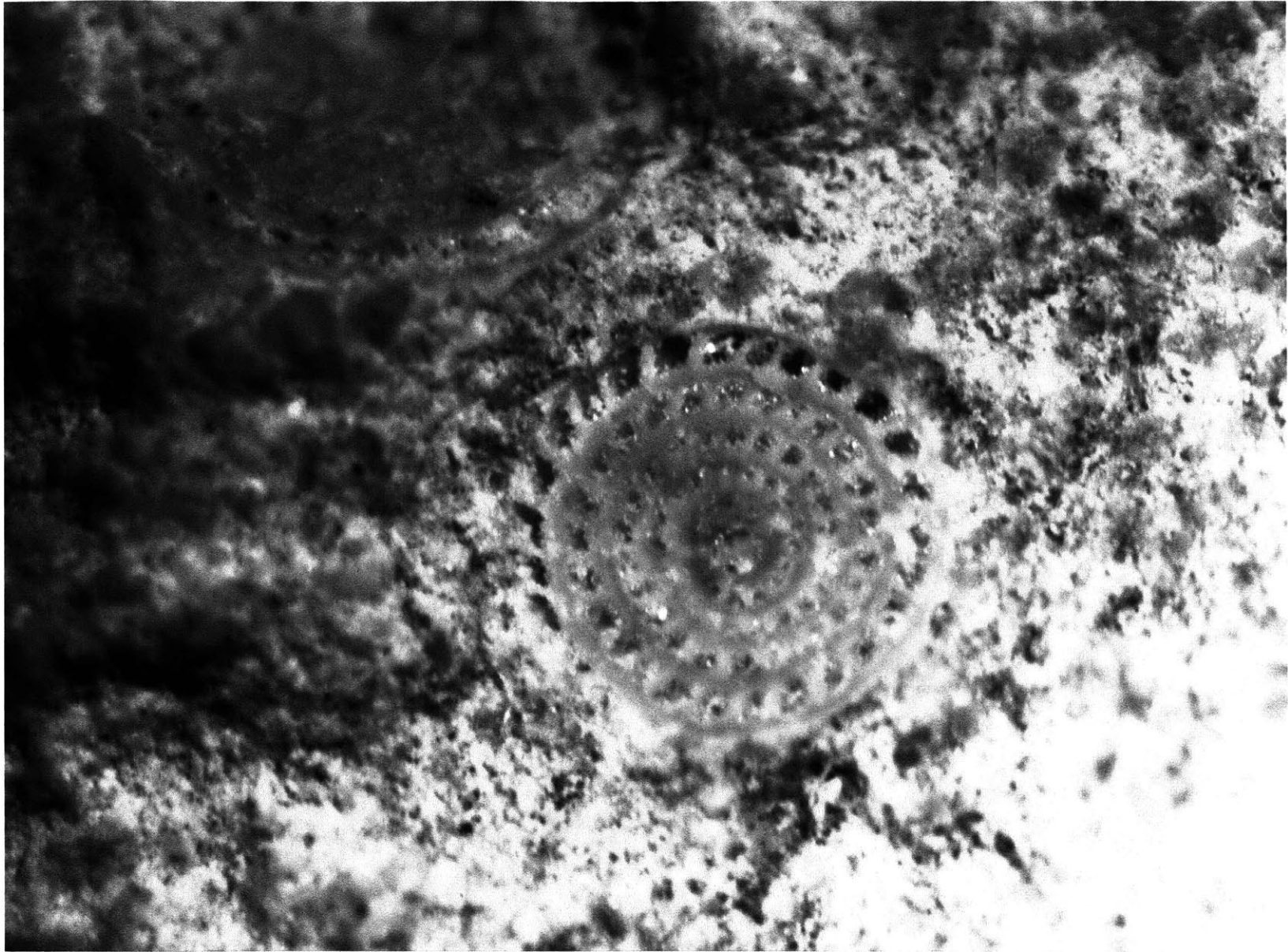
Tile sample 1



MIT cmse

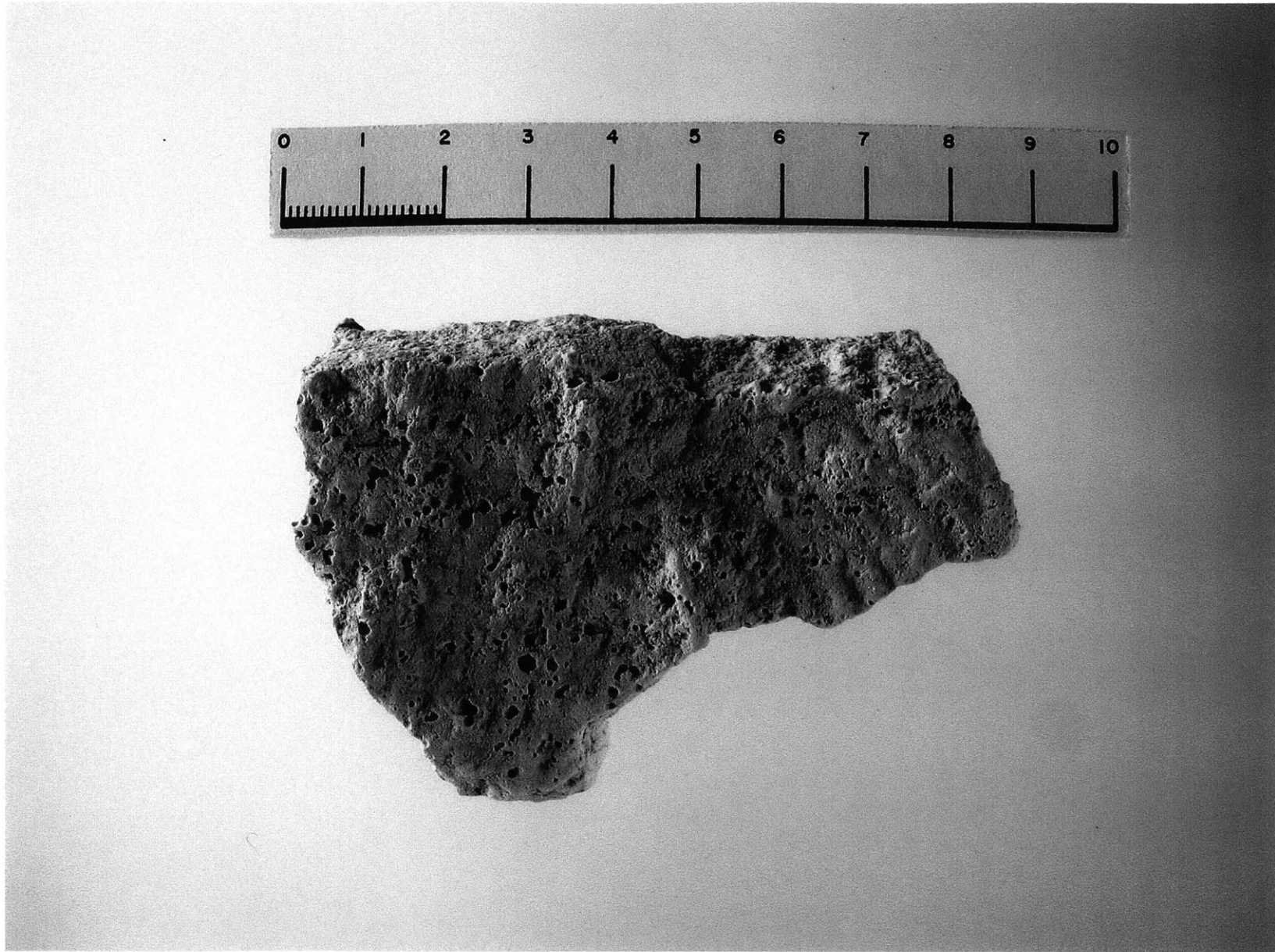
[DATA_4(X-ray Lab)\C:\Data\L\Hobbs> Wednesday, Sep 07, 2005 12:15p (MDI/JADE7)

Results of the analysis for the sample from the upper course of the decoration of Khayer Bek dome in the laboratory of the MIT Department of Material Science by Professor Linn Hobbs



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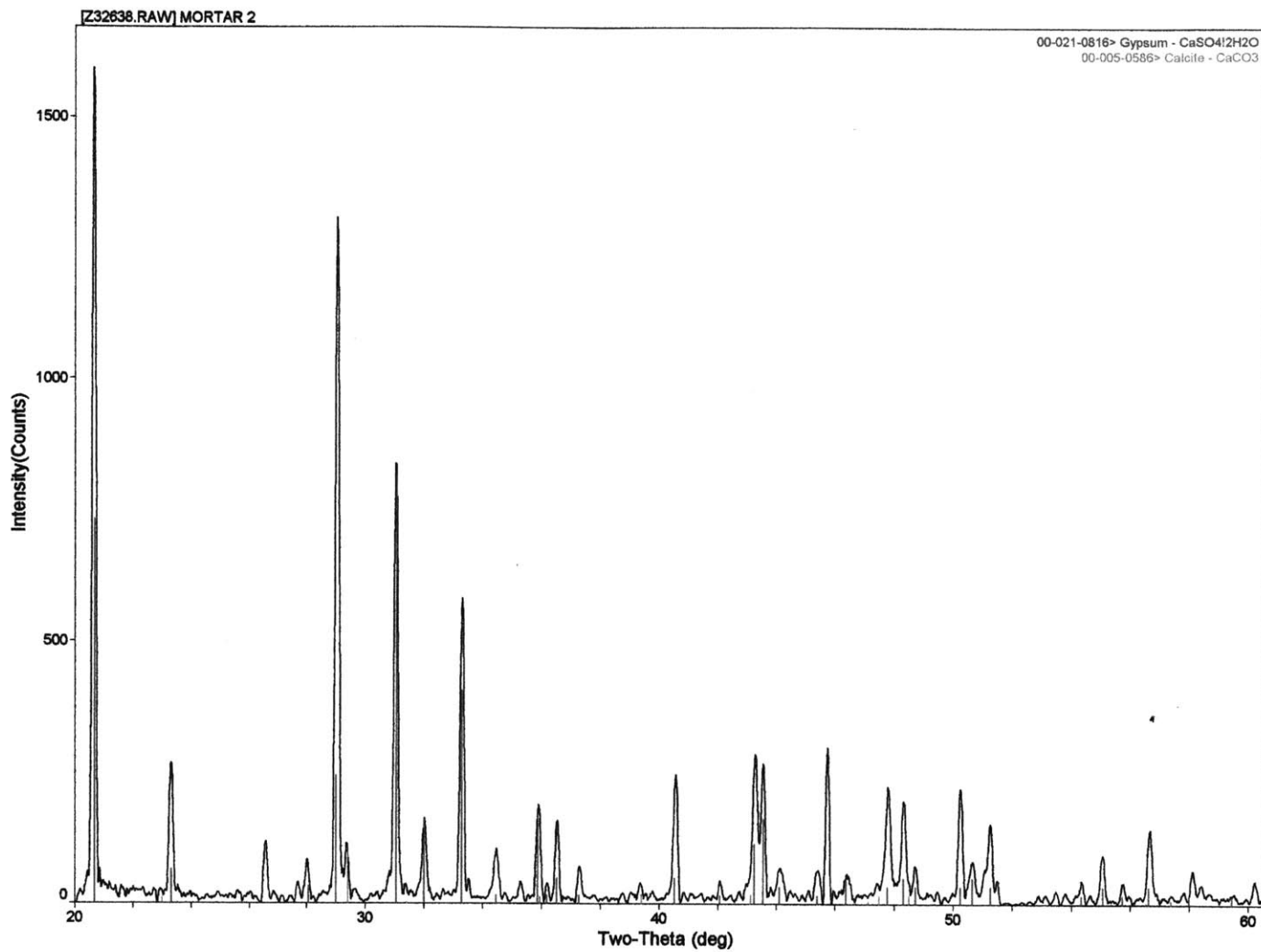
Microscopic image enlarging 16 times the sample of limestone from the upper course of Khayer Bek dome
Analyzed in the laboratory of the MIT Department of Material Science (CMRAE) by Professor Heather Lechtman and Elizabeth Hendrix



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Sample of the gypsum mortar between the joints of the upper course of the dome of Amir Khayer Bek analyzed in the laboratory of the MIT Department of Material Science (CMRAE) by Professor Heather Lechtman and Elizabeth Hendrix

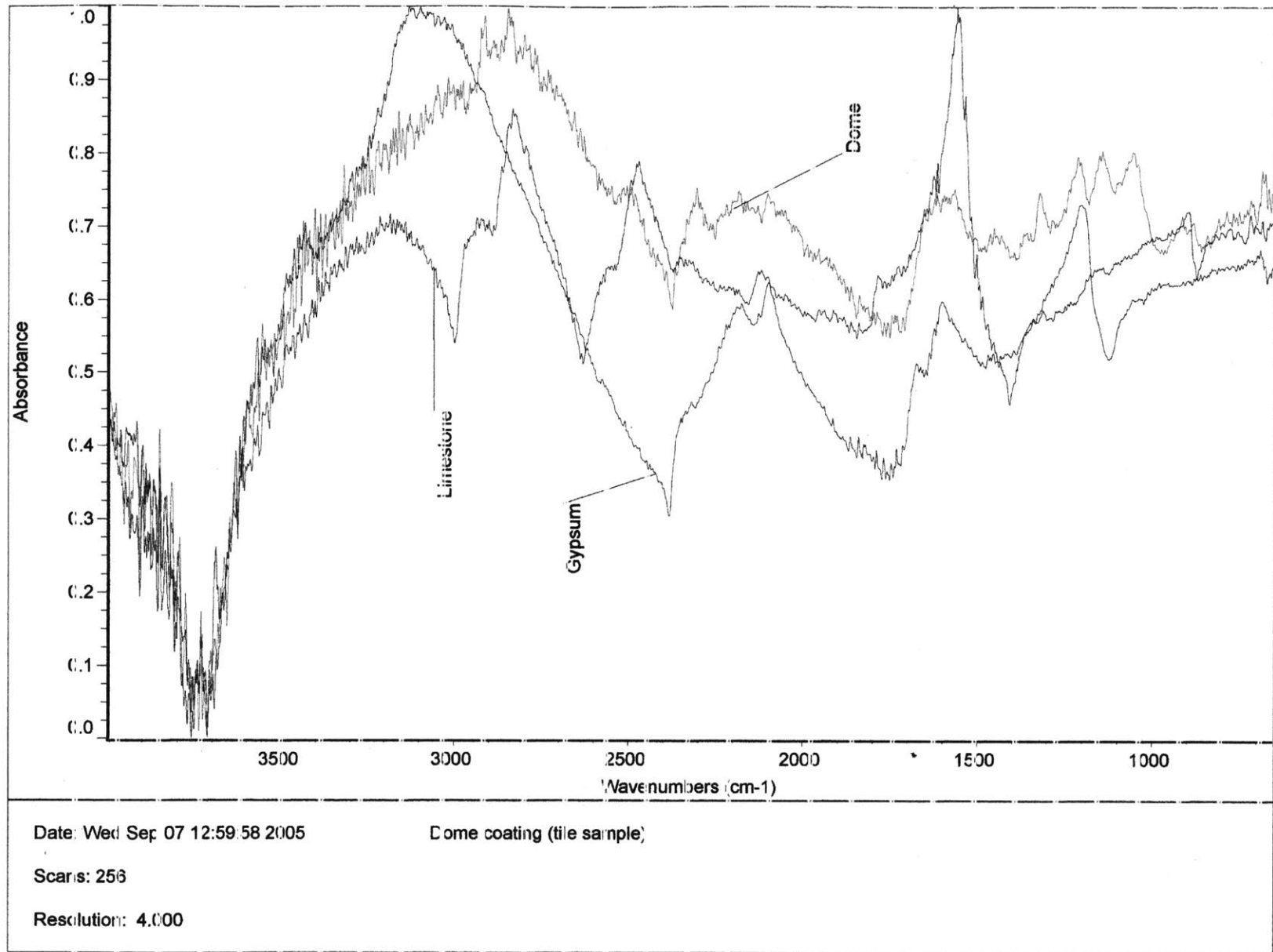
Mortar Large Piece



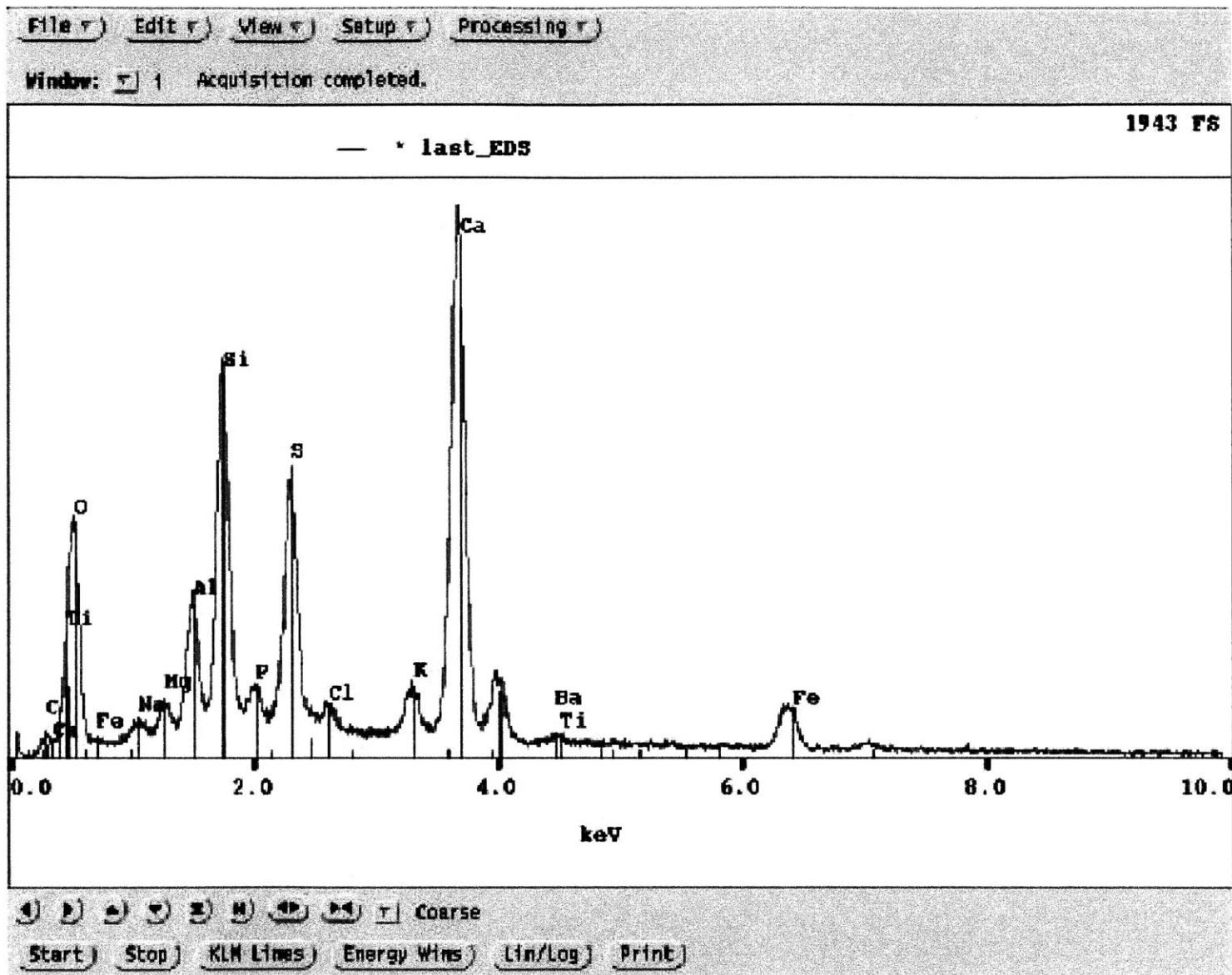
MIT cmse

[DATA_4|X-ray Lab|C:\Data\L.Hobbs> Wednesday, Sep 07, 2005 11:38a (MDI/JADE7)

Sample of the mortar between the joints in the upper portion of the dome of Khayer Bek analyzed in the laboratory of the MIT Department of Material Science by Professor Linn Hobbs



Graphic comparing the spectra of the internal, external portion of limestone and the gypsum mortar.



Chemical analysis of the external crust of the limestone coming from the upper course of the decoration of the dome of Khayer Bek Mausoleum. Conducted by Prof Linn Hobbs in the department of material science at MIT.

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