ber 1992

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Field Investigation of Damage to Islamic Monuments Caused by the Egyptian Earthquake of October 12, 1992

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Introduction

On October 12, 1992, at 3:10 p.m. local time, a magnitude 5.9 earthquake occurred approximately 30 km south of Cairo, Egypt. The last earthquake with a comparable magnitude and epicenter occurred in 1847. Thus, the 1992 earthquake caught the Egyptian people, government institutions and the technical community unprepared. The most severe damage occurred in adobe and stone masonry structures south of Cairo where there were also reports of soil liquefaction. A few modern structures in the Cairo area collapsed and several were damaged. There were approximately 550 deaths and 10,000 injuries as a result of the earthquake.

In response to a call for assistance from the Egyptian Antiquities Organization, three University of Michigan professors from the Department of Civil and Environmental Engineering traveled to Egypt to evaluate damage caused by the earthquake to ancient Islamic Monuments in Cairo. The request for assistance was transmitted to the University of Michigan by the American Research Center in Egypt (ARCE), a consortium of forty-two universities and research institutions interested in studying and preserving ancient Egyptian antiquities. Members of the investigation team were James K. Wight, a structural engineer and specialist on earthquake resistant design, Roman Hryciw, a geotechnical engineer and specialist on earthquake effects on soils, and Antoine Naaman, a structural engineer and specialist on advanced cementitious materials. The team had four full working days in Cairo, October 24-27, during which they visited fourteen sites with varying degrees of damage. They also visited with researchers from the University of Cairo, met with the assistant to the U.S. Ambassador in Cairo and participated in a press conference for the local press and television journalists.

Summary of Findings

The following summary is based on the scope of the investigation the University of Michigan team was able to undertake during their four day period in Cairo. The team developed a good understanding of the important issues regarding the repair and restoration of the Islamic monuments. A more detailed discussion of each site visited by the investigation team follows this brief summary.

The earthquake of October 12, 1992 did cause damage to some of the Islamic monuments, such as cracking in the walls, arches and domes; leaning of minaret towers and corresponding failure of the interface between the minaret towers and the rest of the mosque structure; and partial or total collapse of the tops of the minarets. However, except for the collapse of the tops of the minarets, the damage caused by the earthquake seems to have only added to a long and ongoing process of deterioration that predates the earthquake. The primary reason for such damage is high groundwater. The water is having a deleterious effect on the foundations of many of the monuments, leading to uneven settlements of the foundation and structure. These differential settlements have resulted in sizeable cracking in the walls of several mosques and leaning of minarets.

The foundations for most of the visited structures consisted of placed stone with a silt and mud binder. The foundations are generally greater than 1 meter thick. At several of the visited locations, excavated pits allowed for direct observation of groundwater levels. The water was typically in contact with the stone foundation and no more than 1.5 meters below the ground surface. The binder material is highly erodible in the presence of seepage. Furthermore, the predominantly fine-grained silt causes capillary suction of water up from the phreatic surface. The water rises up into the porous limestone walls of the structures. Dissolution of both the foundation stone and the limestone blocks of the structures is evidently occurring. As the water reaches the surface of the limestone blocks, it evaporates, leaving a powdery precipitate. This yellowish powder was clearly visible in the lower sections of many walls and sometimes reached heights up to 1.5 meters above grade.

While it was clear that the earthquake caused some damage to the cracked walls and the leaning minaret towers, the degree of damage attributed to the earthquake could not be accurately assessed. In most cases the earthquake induced damage was less than twenty-five percent of the total damage observed. The only exception would be the partial or total collapse of the tops of some of the minarets. The ornate tops were generally supported by thin unreinforced columns or posts. Lateral shaking during the earthquake caused several of these supporting elements to fail and the tops crashed to the ground.

Recommendations

The minaret towers at various mosques and the ornate tops of those minarets represent the most important safety issue that must be addressed immediately. The minaret towers that are leaning should be instrumented or monitored to determine if they are still moving. Any that are still moving or appear to be unstable should be supported. The columns and posts that support the tops of the minarets should be strengthened, or the tops should be removed.

A related safety issue is the parapet walls and other appendages attached to the mosques and other buildings. These elements should be checked to determine how well they are anchored to the base structure. If any appear to be loose, they should either be removed or repaired to ensure proper anchorage.

Long term efforts to repair and restore the various Islamic mosques and monuments should be delayed until the high groundwater problem is remedied. Observation piezometers should be installed to various depths to determine whether the near-surface water is perched atop an upper impermeable strata or whether it is contiguous with ground water in a more permeable sub-strata. The possibility of artesian conditions should also be investigated. It is generally known that Cairo is founded on a silty clay layer. The thickness of this clay ranges from zero up to 15 m. A sand layer of much greater thickness underlies the clay. At some locations, silts and clay/silt/sand mixtures may be found between the upper clay and lower sands. The source of groundwater in the sand is the Nile River. However, it has been reported that leaks in the water supply and sewer systems of Cairo are the major contributors to the high water in the clay. There is a plan for a major replacement of Cairo's sewer system. It is clear that this replacement system should include the historic Islamic sections of the city. The hope is that the new system will lead to a regional lowering of the water in the clay layer.

An assessment of the hydrogeologic conditions may also reveal the possibility of other remedial dewatering schemes. For example, if the near-surface water is perched, the water may be drained into the underlying sand layer by drilling holes through the overlying clay. Alternatively, artesian conditions would prohibit such penetration through the clay aquiclude.

Regional groundwater lowering, which should accompany the construction of the new sewerage system, is preferred to local pumping. However, if local pumping is necessary as a temporary measure, great care must be taken to insure that fine soils are not piped out of the foundation layer. The effect of any local ground water lowering on stability of adjacent structures would also have to be addressed. Clearly, if regional ground water lowering is anticipated, local pumping should not be undertaken, except in extreme emergencies.

Prior to either regional or local groundwater lowering, a geotechnical investigation consisting of soil borings, standard penetration and/or cone penetration tests and laboratory testing of retrieved samples must be performed to determine the impact of the water lowering. Since ground water lowering will increase effective stresses in the soil, some additional settlement of structures should be expected. It is imperative to ascertain the compressibility characteristics and stress history of the soils underlying the mosques to quantify these anticipated settlements. The results of standard penetration or cone penetration tests should also be used to investigate the potential of the lower sand strata to liquefaction during future earthquakes. Such analyses are routine for seismic regions. During and following ground water lowering, ground settlements should be monitored to determine when structural repairs may commence.

Once settlements associated with ground water lowering have ceased, structural repair and restoration efforts can proceed. Cracks in walls, arches, and domes should be repaired to reestablish continuity of these structural systems. Also, continuity needs to be restored between various elements to ensure that the structure is tied together for resisting future seismic events.

When necessary, inclined minaret towers can be straightened, probably by jacking at the foundation level. The upper levels of the minarets should be reinforced to resist potential lateral accelerations from future earthquakes. If a minaret tower is attached to an adjacent mosque, the portion of the minaret tower extending above the level of the adjacent mosque is particularly vulnerable. In lieu of a dynamic analysis, this portion of the minaret should be reinforced to carry a lateral force equal to the mass of the minaret above this level multiplied by ten percent of gravity. This force should be applied at a point two-thirds of the distance from the level of the adjacent mosque to the top of the minaret. For safety of the very tops of the minaret, a similar requirement should be applied whenever there is a significant change in the cross section of the minaret.

Observations at Specific Sites

Sultan El Ghuri Complex

Our guide, Dr. Abdallah Al-Attar, indicated that the El Ghuri complex was one of the most important Islamic sites in Cairo and that it had a significant amount of damage. Because of its importance, our investigation team spent approximately three hours at this site. Most of the time was spent studying the exterior and interior of the mosque and the minaret tower.

The height of the mosque was approximately equivalent to a four story building with a minaret tower attached to the southeast corner (Fig. 1). Cracks were visible on all external faces of the mosque. There was one very large crack at a reentrant corner along the east wall where the minaret tower was connected to the mosque (Fig. 2). This appeared to be an old crack that was clearly related to uneven settlement that resulted in the minaret tower leaning slightly away from the mosque. Any increase in the width and length of this crack due to the earthquake could not be determined.

A crack in the south wall, approximately thirty feet away from the southeast corner of the mosque, was observed to be wider near the base of the mosque than at the top (Fig. 3). This crack seemed to indicate uneven lateral movements near the base of the mosque. Again, there was no clear evidence that the earthquake had significantly changed the width and length of this crack.

On the west side of the mosque there were numerous windows and reentrant corners. Cracks were clearly visible in several locations (Figs. 4 and 5). All of these cracks seemed to be old cracks and were certainly not caused by the earthquake. Plaster strips had recently been applied across some of these cracks (Fig. 5). It was reported that the strips were all applied within the last three months before the earthquake. The strips had been placed across the cracks to study movement along or across the cracks due to settlement or other causes. However, in this case they served as an excellent indicator of movements due to the earthquake. The plaster strips shown in Fig. 5 appeared to be undamaged.

One other concern was the safety of the ornamental parapet wall around the top of the mosque. In some cases cracks in the walls extended up through the parapet (Fig. 4). It appeared that portions of the parapet could fall during a significant aftershock or future earthquake.

Inside the mosque there were more cracks and numerous plaster strips across several of the cracks (Fig. 6). Again, most of the plaster strips were not broken. Of the ones that were cracked and could be observed closely, the width of the cracks in the plaster strips varied between 2 to 5 mm. These strips were spanning cracks that varied in width from 15 to 40 mm.

There were several archways within the mosque and some of them had significant damage (Figs. 7 and 8). It was reported that some of the ornate material attached to these archways had fallen during the earthquake. Plaster strips had again been applied across some of the preexisting cracks in the arches and the majority of the strips had not been broken. In some of the smaller archways the keystone was loose. At these locations plaster strips had been applied across the cracks and the keystone had apparently been braced before the earthquake. It appeared that additional damage to these archways during the earthquake was small.

At some wall intersections, both inside and outside of the mosque where plaster strips had also been applied, the strips were broken in a manner that indicated more significant differential movement between the adjacent walls during the earthquake (Fig. 9). These movements seemed to indicate that due to the preexisting cracks, continuity between these walls had been lost. Thus, they moved independently during the earthquake.

There were some excavations in the foundation below the mosque. In each hole, water was present within one meter of the base of the foundation (Fig. 10). The limestone blocks in and just above the foundation level were discolored, indicating capillary rise from the groundwater level. This water partially dissolves the limestone and when it evaporates on the exposed surfaces, it leaves behind a yellowish mineral deposit. In some cases the discoloration extended more than one meter above the top of the foundation.

In summary, the mosque of El-Ghuri was definitely cracked significantly before the earthquake. The minaret tower was also probably leaning before the earthquake, but the exact before and after states could not be established. The damage before the earthquake was probably caused by uneven settlements which are directly related to the high groundwater level at the site. It was reported that the high groundwater level is a relatively recent problem, having developed within the last twenty years. The mosque and associated buildings can be structurally repaired, but the problem with the high groundwater table and the resulting settlements must be solved first. Structural repair and restoration of the mosque must reestablish continuity within and between the massive bearing walls. The ability of the mosque to safely resist future seismic events is compromised by the numerous existing cracks that uncouple the various parts of the mosque walls.

El-Dashtwati Mosque

The dome of the El-Dashtwati Mosque collapsed during the earthquake (Fig. 11). At the time of the team's visit, debris from the dome was still on the ground, either inside the tower structure, which had been covered by the dome, or outside on the street (Fig. 12). A crew from the Egyptian Antiquities Organization had cleared around the dome support ring to eliminate the danger from falling debris. The dome structure had been constructed using two layers of bricks and mortar. The dome covered a tower about three stories high. The overall building was approximately square, with the tower part occupying a quarter of the area near one corner. The team was told that the mosque was built during the Turkish empire at the end of the 18th or early in the 19th century. The structure was primarily stone masonry. Several cracks were observed along the walls, some of which were clearly present prior to the earthquake (Fig. 13). It was the team's opinion that the cracks could be patched, the structure repaired, the dome ring strengthened, and the dome rebuilt using either restoration materials or modern materials.

Al-Hanafi Mosque

The most significant damage at the Al-Hanafi Mosque was the collapse of three of four ornate columns at the top of the minaret tower. The one remaining column is shown in Fig. 14. The other three columns failed during the earthquake and crashed onto the street below (Fig. 15). There was no indication of any reinforcement in the columns and the ornate tops seemed to be a series of unreinforced stone slices placed on top of each other (Fig. 15 b). There was a single dowel bar running through a small diameter hole in the center of these slices, but it was not grouted in place. The dowel bar was apparently used to align the slices, but not intended to offer shear or moment resistance for the ornate top.

The one column at the top of the minaret tower should be removed or attached more securely to the tower. All four columns can be easily replaced, but the new columns must have a basic seismic resistance to lateral accelerations as described in the section on recommendations.

Mosque of Sultan Khani Bey El Rama

Among all of the sites visited, the mosque of Sultan Khani Bey El Rama was in the worst condition. It provided the most dramatic evidence of the repercussions of inappropriately controlled local dewatering. It was reported to the inspection team that during local pumping to draw down the water, the mosque's minaret tilted, rotated and collapsed. The location where the minaret tower broke away from the mosque is shown in Fig. 16. Local residents recount that as the minaret was falling, the decorative top of the minaret was launched as an airborne projectile (due to centripetal acceleration). Two individuals in a house across the street from the mosque were reported to have been crushed by the projectile. While the inspection team could neither confirm nor find contradiction to this account, it was very evident that the collapse predated the earthquake. If dewatering was the culprit for the collapse, it is very likely that the drawdown was too rapid, thereby inducing high hydraulic gradients which piped fine grained soil out of the foundation.

The overall state of the Khani Bey Mosque was very poor (Fig. 17). Groundwater was visible in an open pit at less than one meter depth (Fig. 18). Differential settlements were in evidence. Access to much of the building was difficult because of collapsed stairways, imposed barriers and debris. Any earthquake induced damage was indistinguishable from other damage. Some walls have been shored in an attempt to prevent further collapse. Many interior areas are dangerous. Repair and restoration of this mosque would be very difficult if not impossible.

Sultan Mahmoud Takkayah Preschool

This structure was apparently a sort of convent where the Dervishes came for temporary retreat from the outside world. It is about 250 years old. In the present, it serves as a preschool. It is a one story high square structure with an open interior courtyard and garden (Fig. 19). Rooms are aligned along the periphery of the square. They all open on the inside to a covered corridor surrounding the courtyard. The roof structure is made of a series of masonry domes and arches. Several wide cracks were observed on the inside of the domes and in some rooms the mortar covering on the inside of the brick dome had spalled off and fallen (Fig. 20). Several cracks in the walls, domes and arches probably existed prior to the earthquake, but were amplified by it (Fig. 21). Most of the cracks could be structurally repaired and patched, restoring the structure to at least its pre-earthquake condition.

Court Building in Citadel near Mohammed Ali Mosque

The facade of this court building had several severe cracks. In particular, the arches of the roof structure covering the porch were in a state of semi-collapse, held together by few shores (Fig. 22). There was evidence that part of the damage was present prior to the earthquake as indicated by a shore that was holding a loose keystone at the top of one of the arches. Since the stones of the facade were still in excellent condition, the team concluded that there should be no problem in restoring the structure to its original service condition.

Mosque Al-Kadi Yahya (Habbaniya District)

The Al-Kadi Yahya Mosque was in good shape, but the minaret tower was leaning noticeably toward the street (Fig. 23). Scaffolding had been erected in the street to support and arrest any future movement of the minaret. An inspection of the circular portion of the minaret tower that projected above the roof of the mosque revealed a continuous crack running around the perimeter of the circular section. The crack had sharp edges, indicating that it was caused by tension, but in a couple locations there were small compression spalls along the crack (Fig. 24). Thus, the cracked had apparently opened and closed at least once during the earthquake as the tower shook back and forth in response to the ground motion. The interior of the mosque and minaret tower were not inspected.

Amir Shaykhu Minaret and Mosque

The top of the minaret tower partially collapsed during to the earthquake (Fig. 25). The team was only able to observe the failure from far away. The top of this minaret should be removed and replaced with a more properly designed ornate top. A second minaret tower, which had a very similar top, was located across a narrow street from the minaret with the partially collapsed top. The top of this second minaret should be inspected and modified for increased seismic resistance.

Mosque Sarghatmish Minaret

The minaret of this mosque showed a very slight inclination, which was noted by the team. However, in the very brief time allocated, it was not possible to determine whether this inclination was induced by the earthquake or existed prior to its occurrence.

Hasan-Bacha Taher Mosque

The exterior of the mosque had minor cracking, but the minaret attached to the front of the mosque was leaning noticeably toward the street. Scaffolding had been erected to support the minaret to prevent further movement. There was no inspection of the interior of the mosque or minaret tower.

Sultan Hasan Madrasah and Mohammed Ali Mosque

The team briefly visited these mosques and was told that the earthquake did not induce any damage in these magnificent structures.

The Coptic Churches in Old Cairo

The inspection team also visited a few Christian Coptic churches in Old Cairo. Among the sites visited here were Abu Sarga (St. Sargius) and Sitt Barbara (St. Barbara). While no earthquake damage was evident here, the groundwater in Abu Sarga was within one half meter of the ground surface. The basement floor of the church was completely inundated. A rock floor in the church appeared damp in some places, suggesting capillary rise of the water. A church caretaker attributed the high water level to the construction of Aswan Dam (and therefore a higher regular Nile River flow). Since Old Cairo is immediately adjacent to the Nile south of Geziret El Roda, this claim may have some merit. Reference to topographic maps for this part of town could verify this hypothesis.

Acknowledgements

Travel costs for the research team were covered by the University of Michigan College of Engineering and all expenses in Egypt were covered by the Egyptian Antiquities Organization (EAO). The investigation team is thankful for the support provided by the following individuals: Dr. Mohamed Ibrahim Bakr, Director of the Egyptian Antiquities Organization, who served as our host in Egypt; Dr. Abdallah Al-Attar, General Director of the EAO who is responsible for Islamic Monuments and who served as our guide to the monuments; Mark Easton, Director of the American Research Center in Egypt, who assisted with local arrangements and served as our contact to the EAO and the U.S. Embassy; and Terry Walz, Director of ARCE in New York, who assisted with travel arrangements and initial contacts in Cairo.

Special thanks are due to Dr. Mohamed E. Sobaih, Professor of Civil Engineering at the University of Cairo and President of the Egyptian Society for Earthquake Engineering, Dr. Tarek A. Macky, Professor of Civil Engineering at Ain-Shams University and Dr. Mohamed G. Al-Tbiary, Professor of Geology at University of Tanta. These three professors were kind enough to meet with the investigation team and provide technical information of relevance to the team's mission.

Fig. 1 Sultan El-Ghuri Mosque and minaret tower

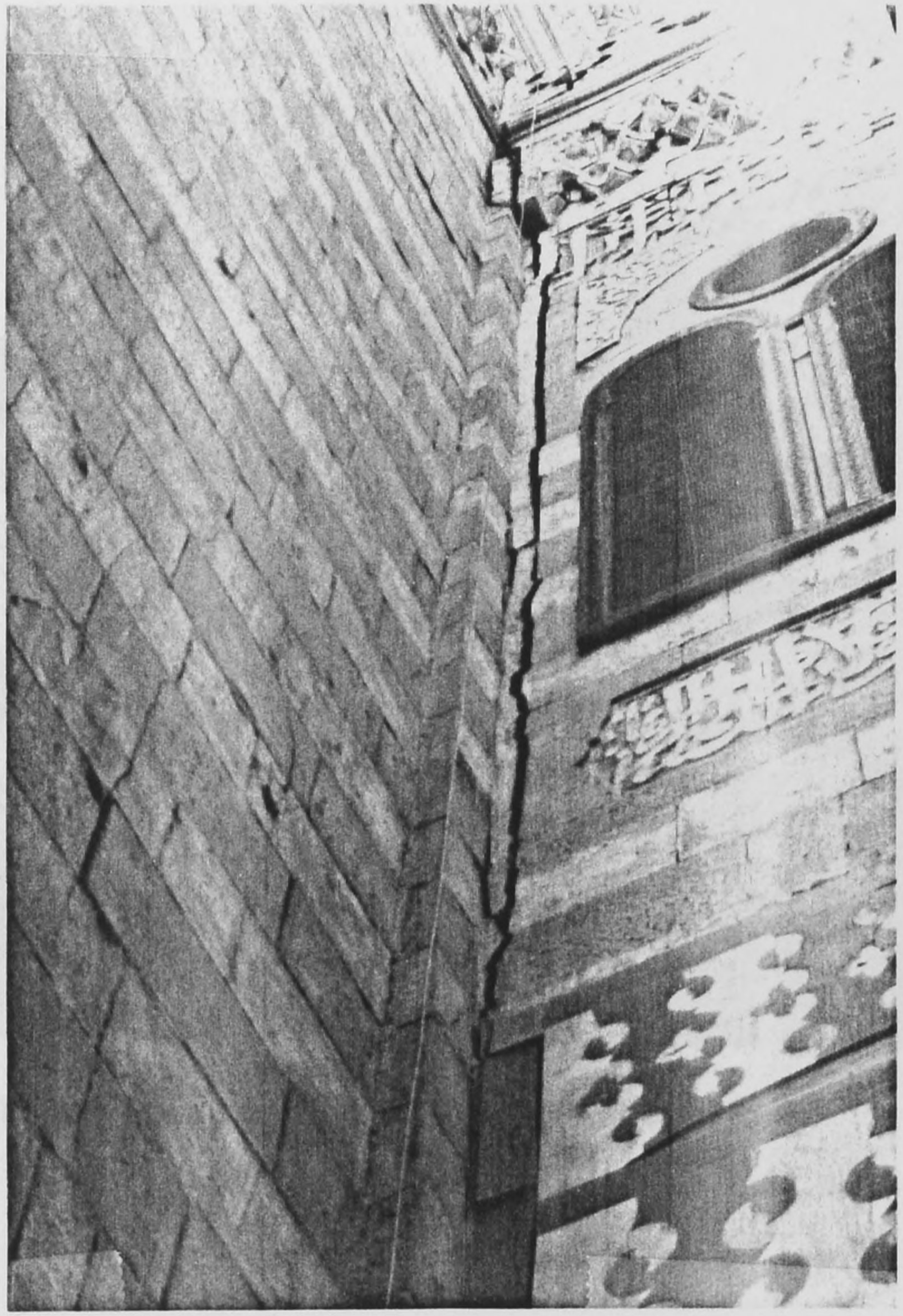


Fig. 2 Crack between minaret tower (left) and mosque

Fig. 3 Crack along south wall of El-Ghuri Mosque

Fig. 4 Cracks in west wall of El-Ghuri Mosque

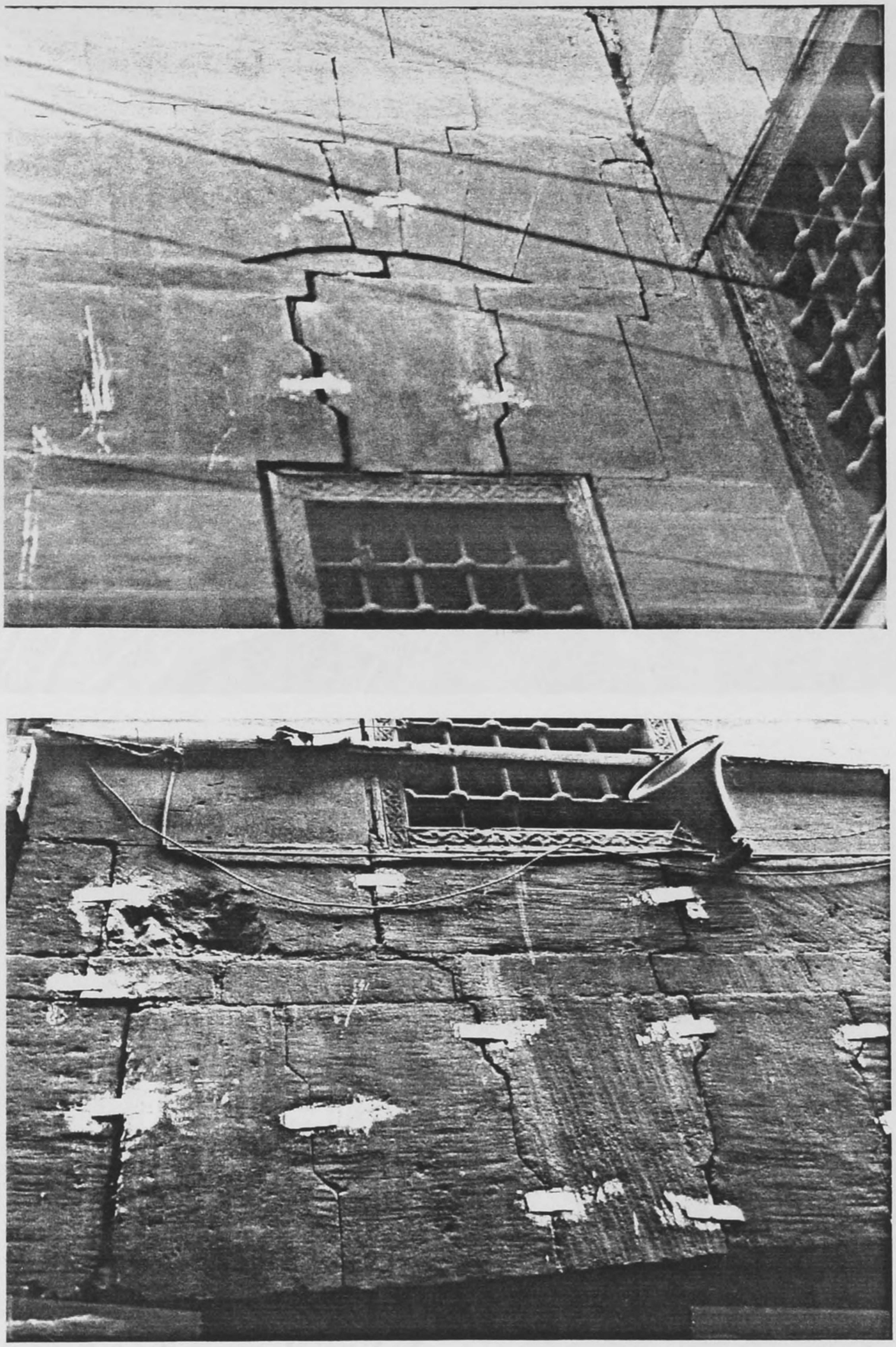


Fig. 5 Plaster strips across cracks in west wall of mosque

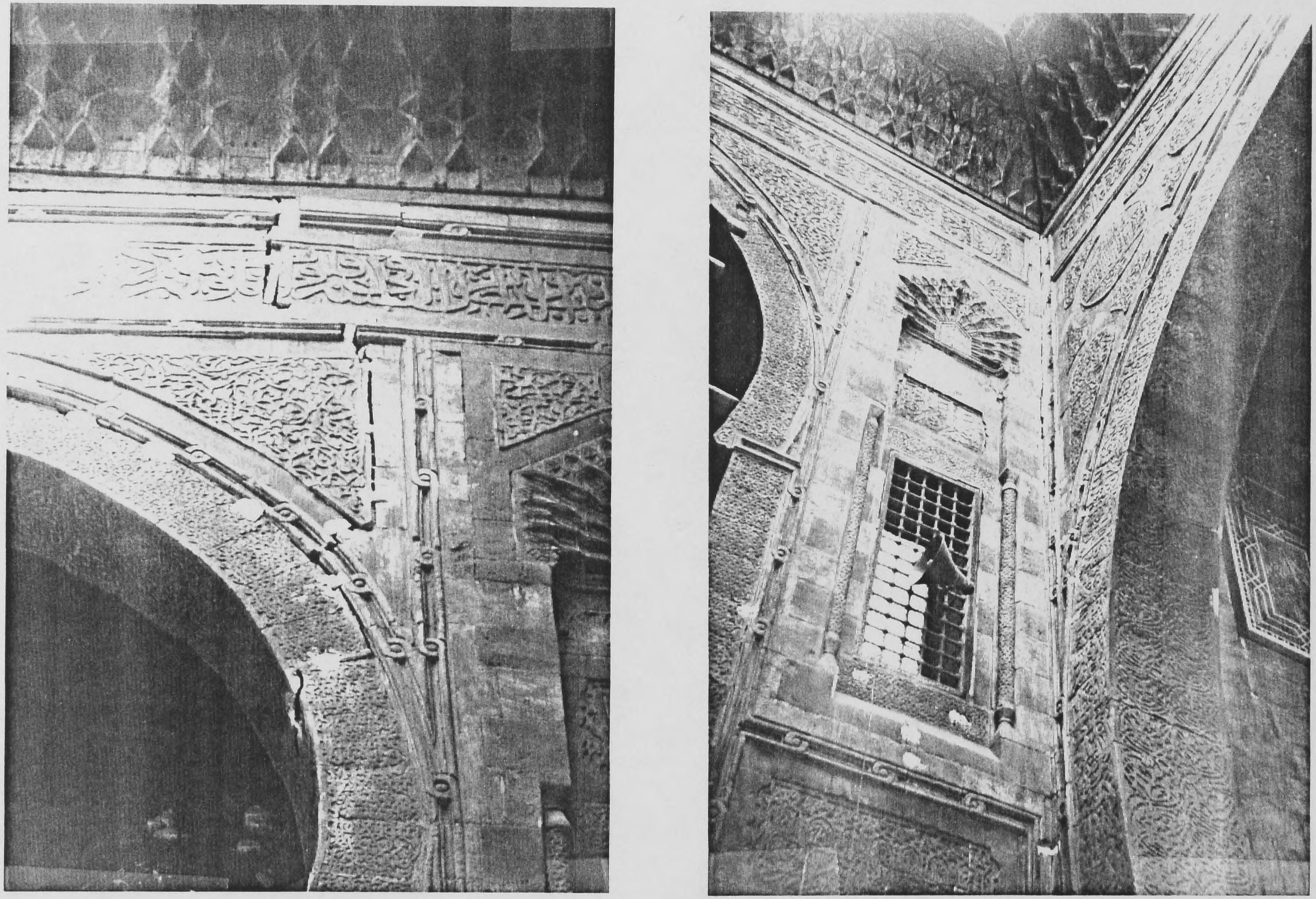


Fig. 6 Interior of El-Ghuri Mosque with plaster strips across some of the cracks

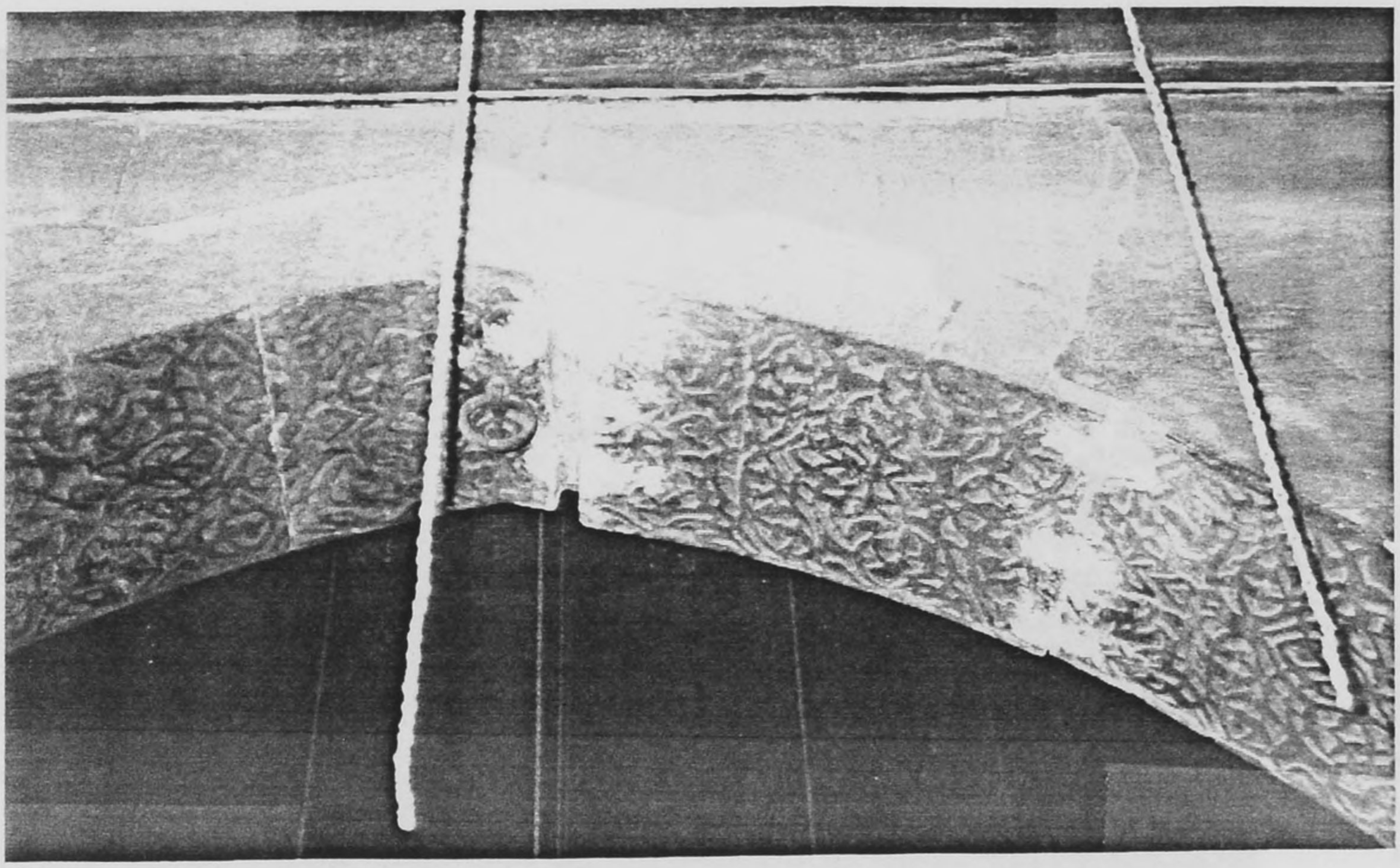


Fig. 7 Major archway across interior of El-Ghuri Mosque

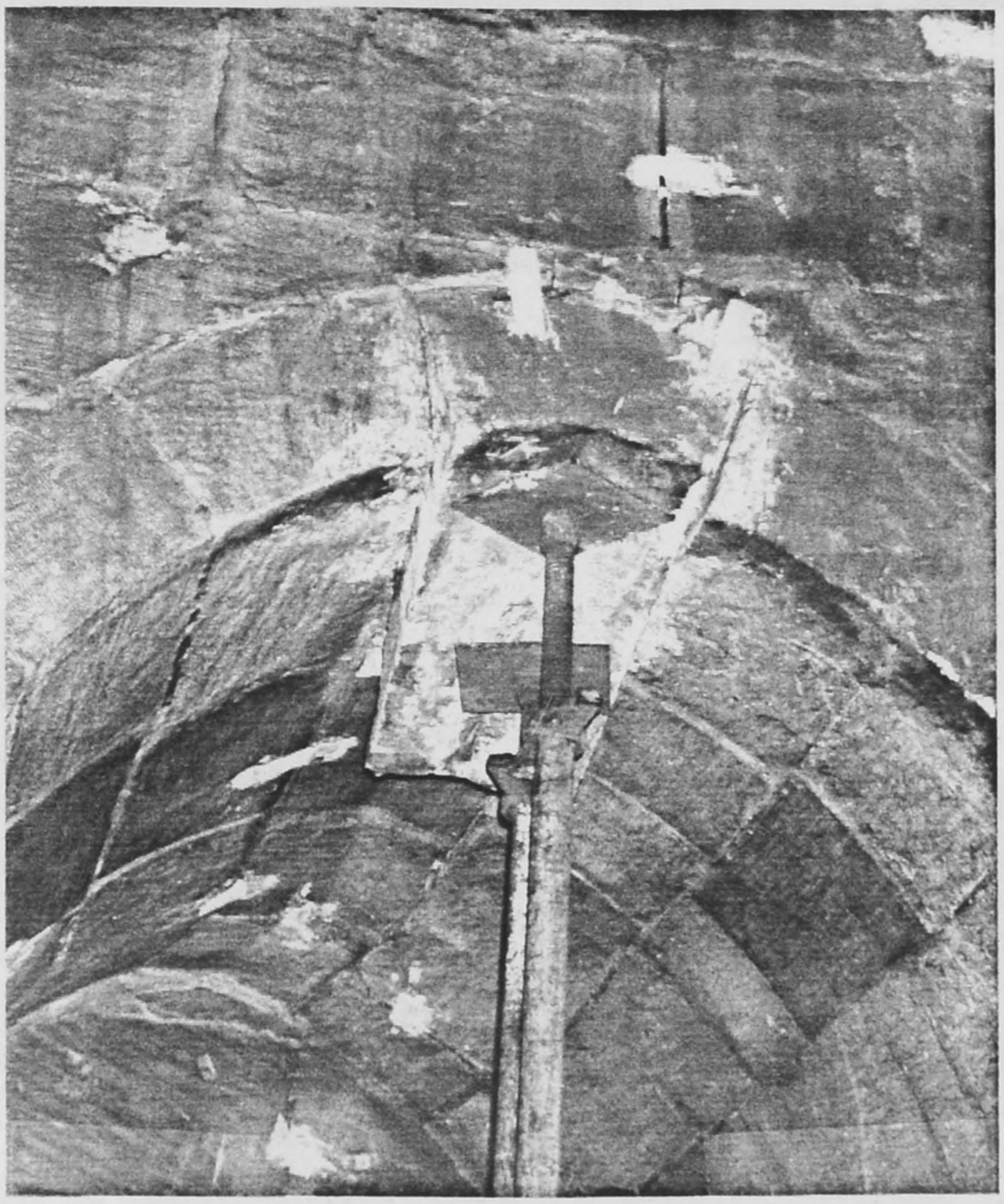
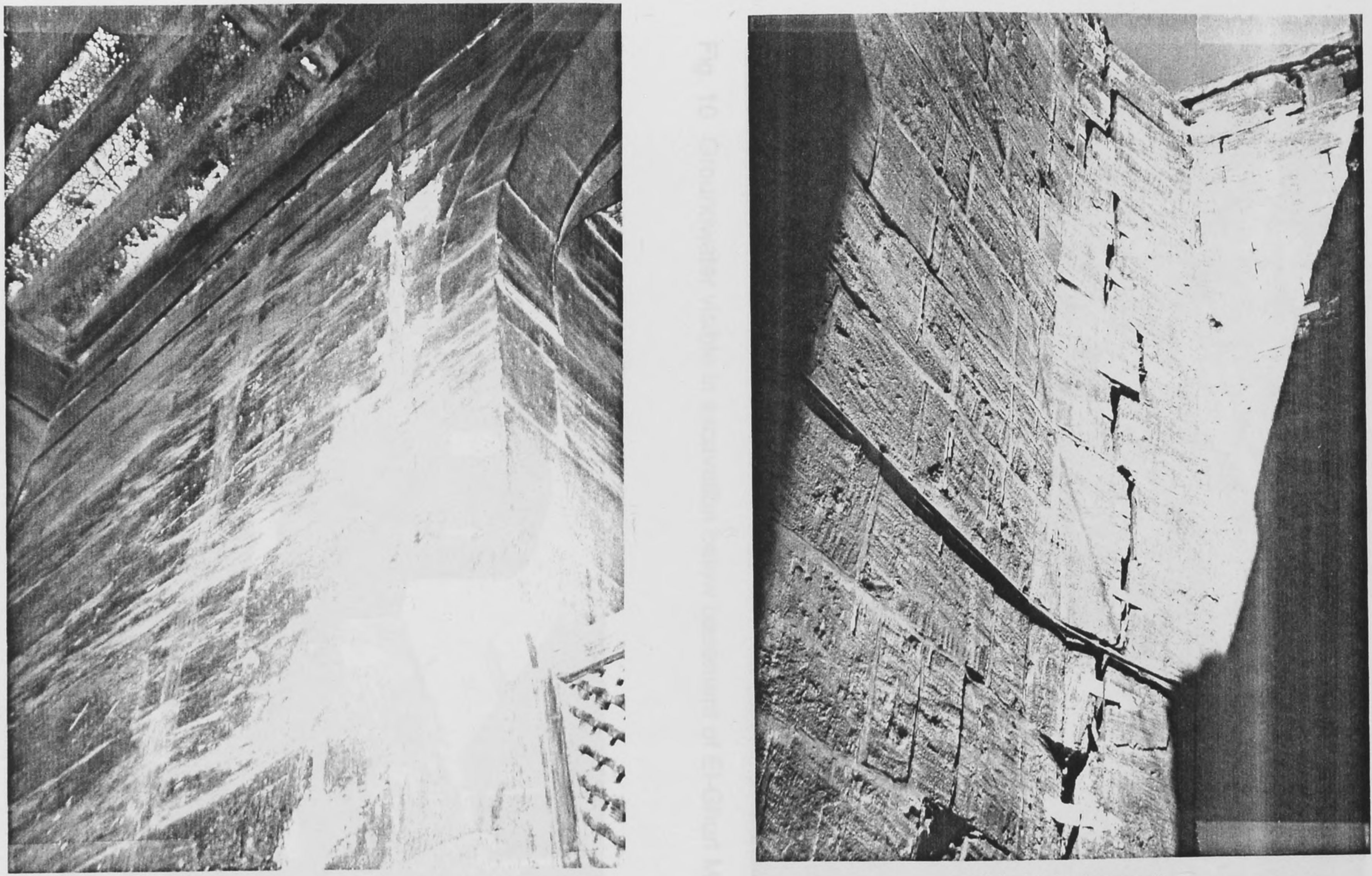


Fig. 8 Loose keystone in arched ceiling over hallway



(a) Interior walls

(b) Exterior walls

Fig. 9 Cracks at wall intersections of El-Ghuri Mosque

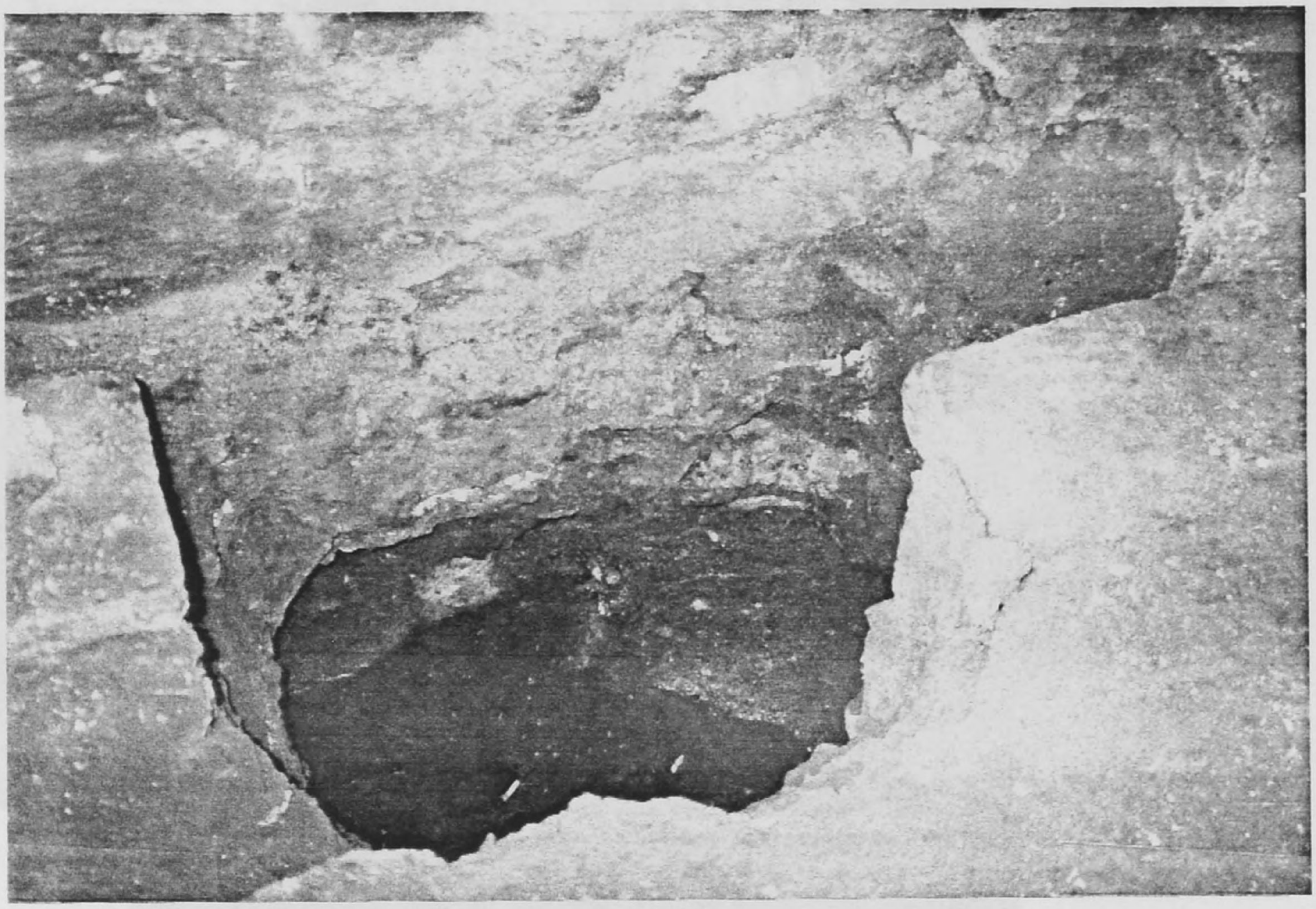
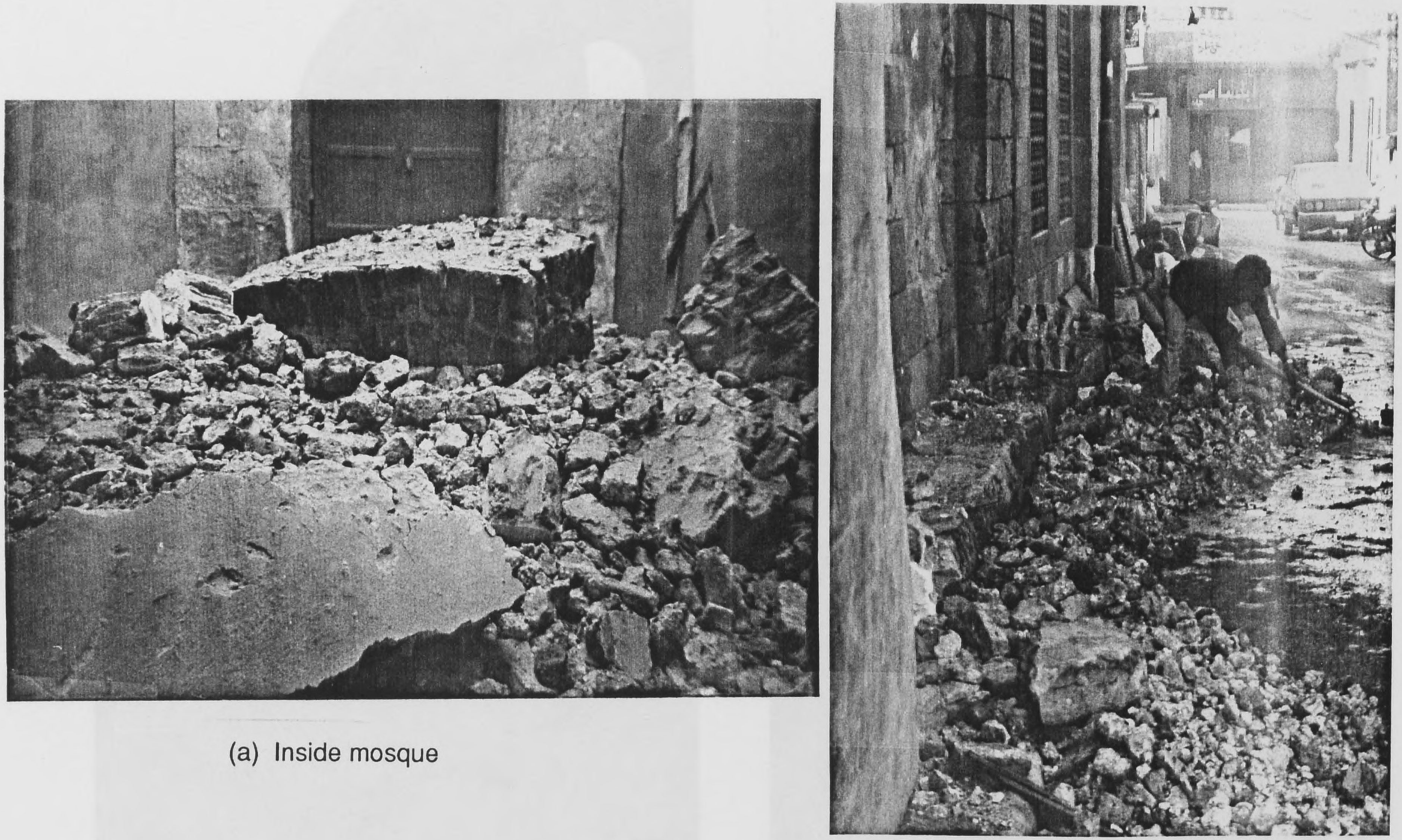


Fig. 10 Groundwater visible in excavation below basement of El-Ghuri Mosque

Fig. 11 Collapsed dome of El-Dashtwati Mosque



(a) Inside mosque

(b) Street adjacent to mosque

Fig. 12 Debris from collapsed dome at El-Dashtwati Mosque

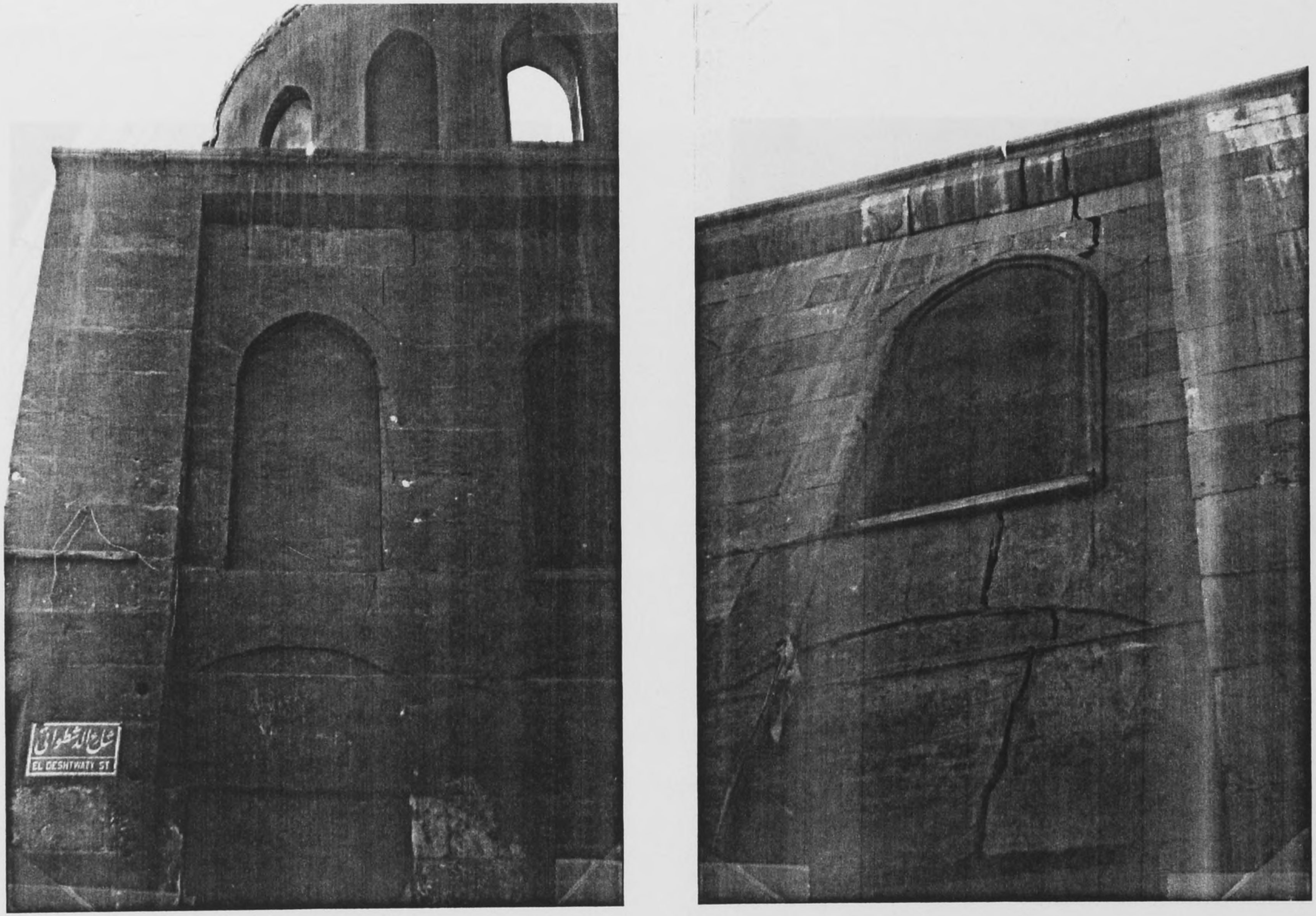


Fig. 13 Cracks in walls of El-Dashtwati Mosque

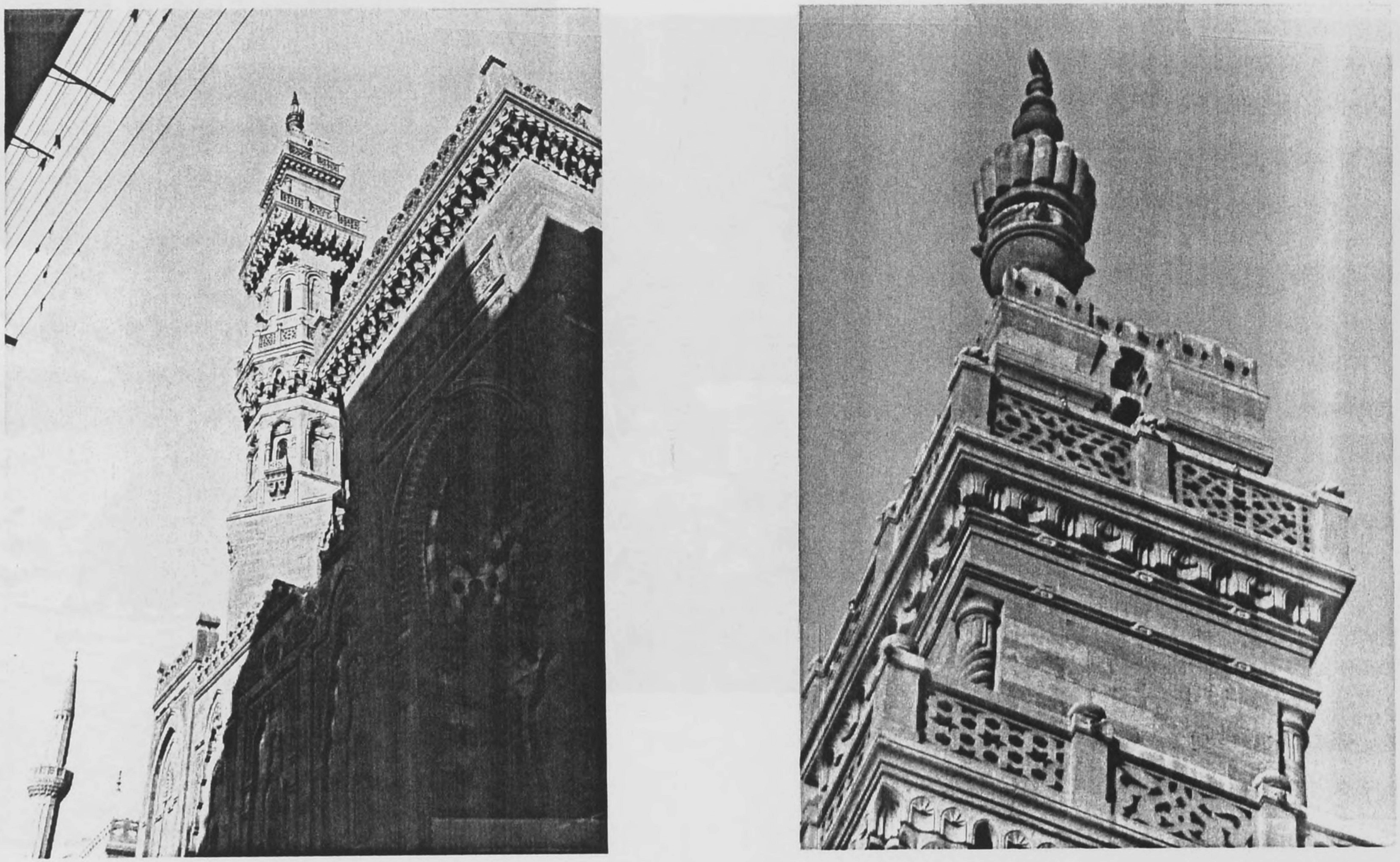
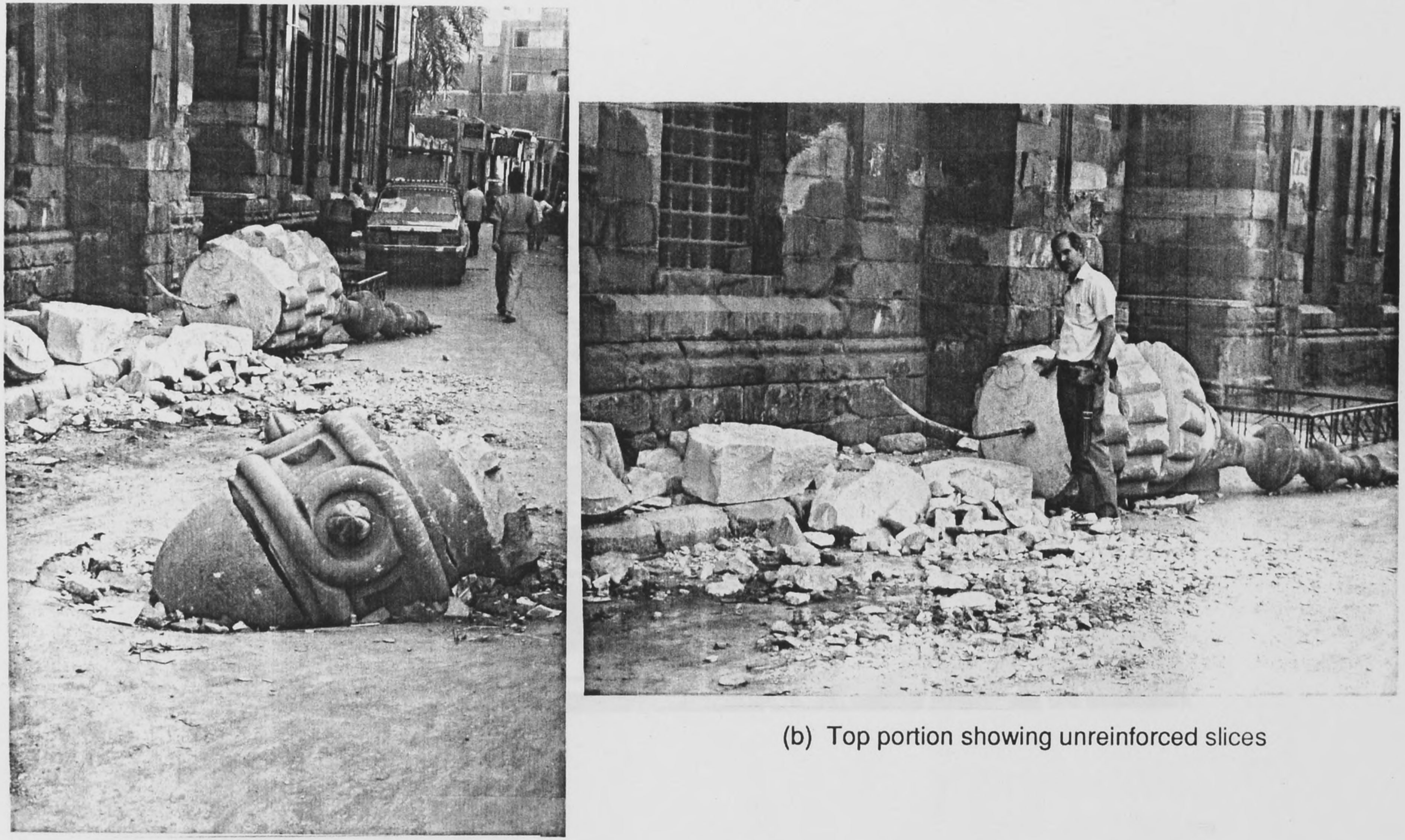


Fig. 14 Minaret tower at Al-Hanafi Mosque with one remaining ornate column



(a) Lower portion of ornate column

(b) Top portion showing unreinforced slices

Fig. 15 Debris from collapsed minaret tops in street adjacent to mosque

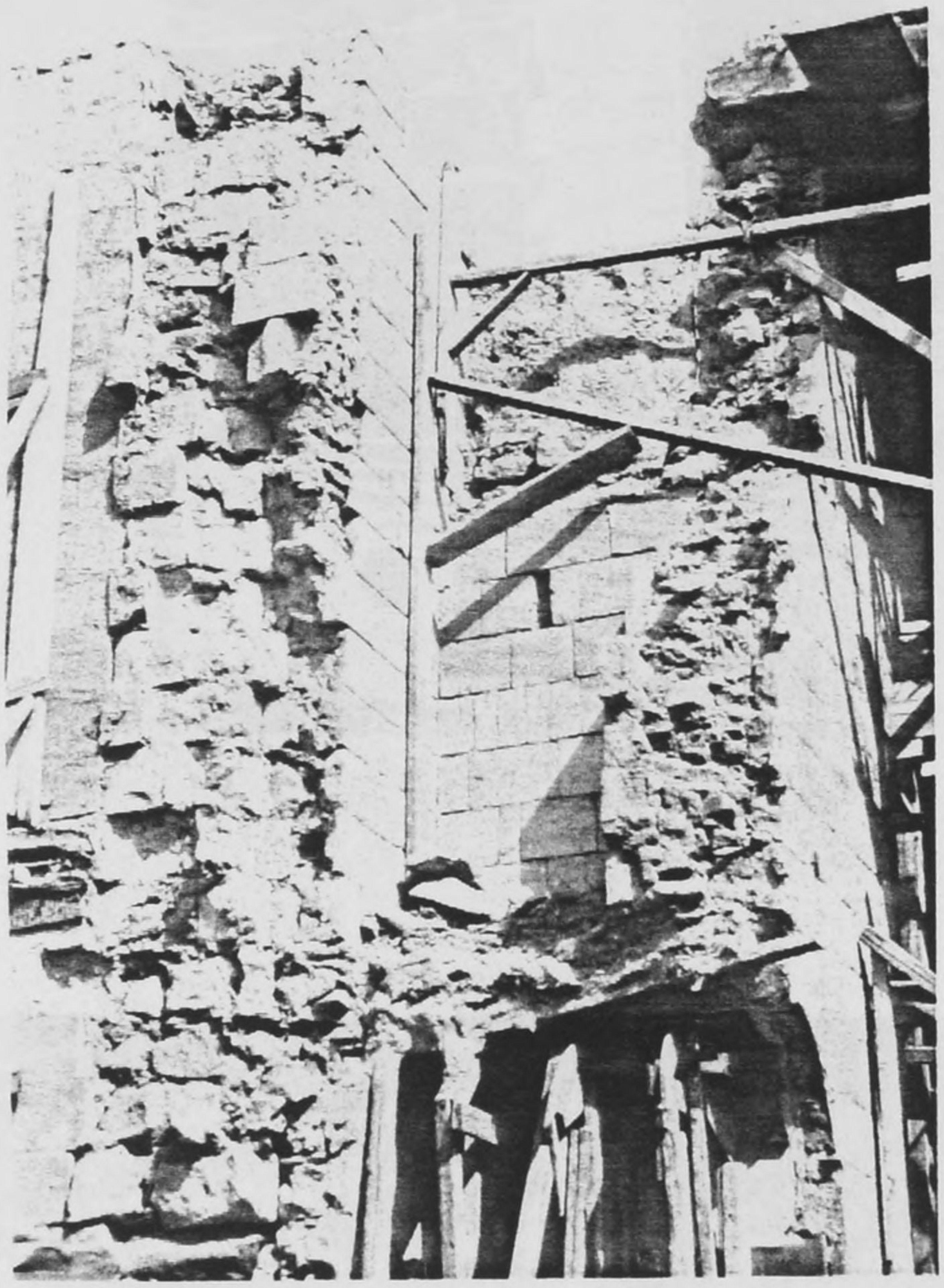


Fig. 16 Location where minaret tower broke away from Mosque of Sultan Khani Bey

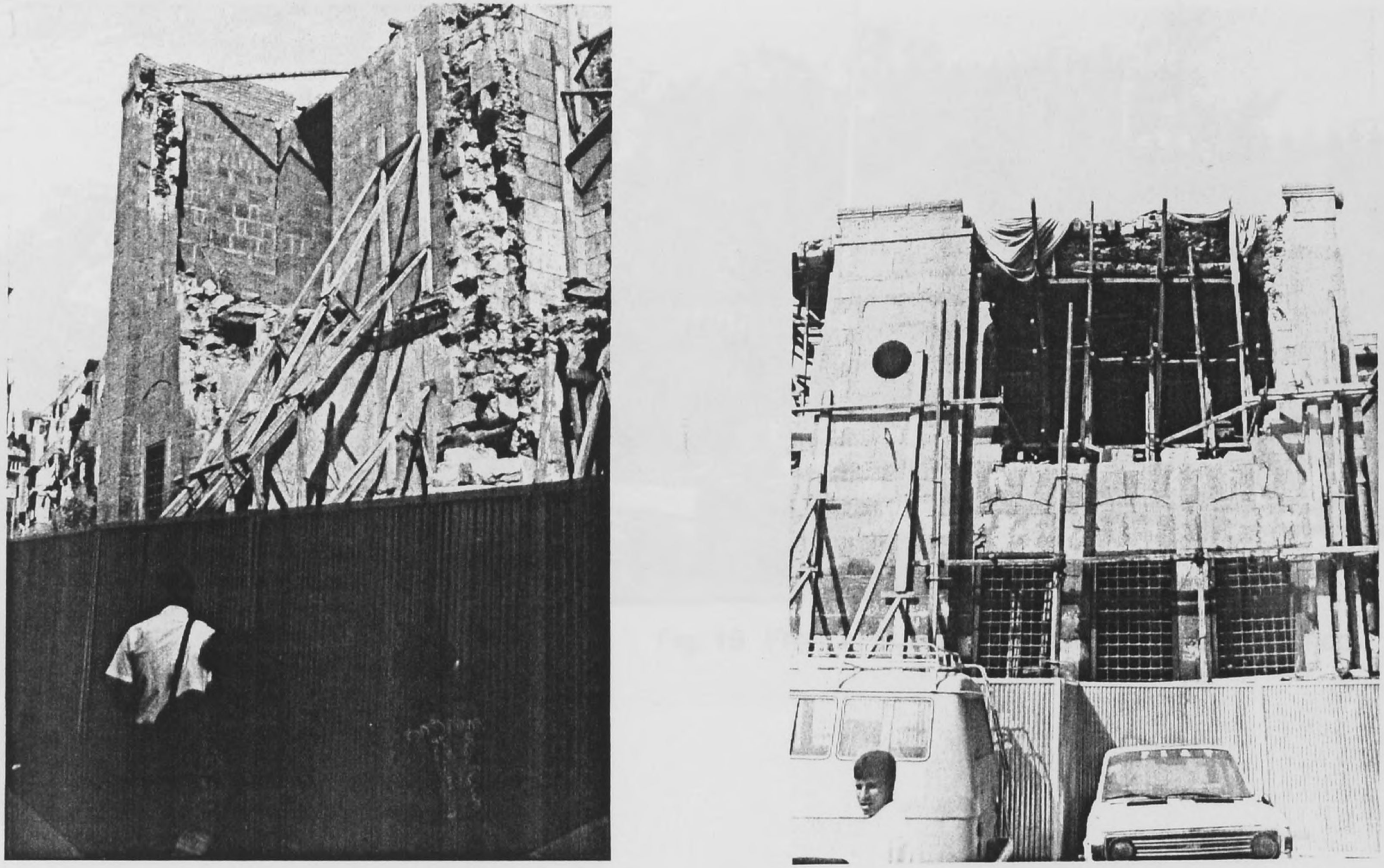


Fig. 17 Deteriorated state of Khani Bey Mosque

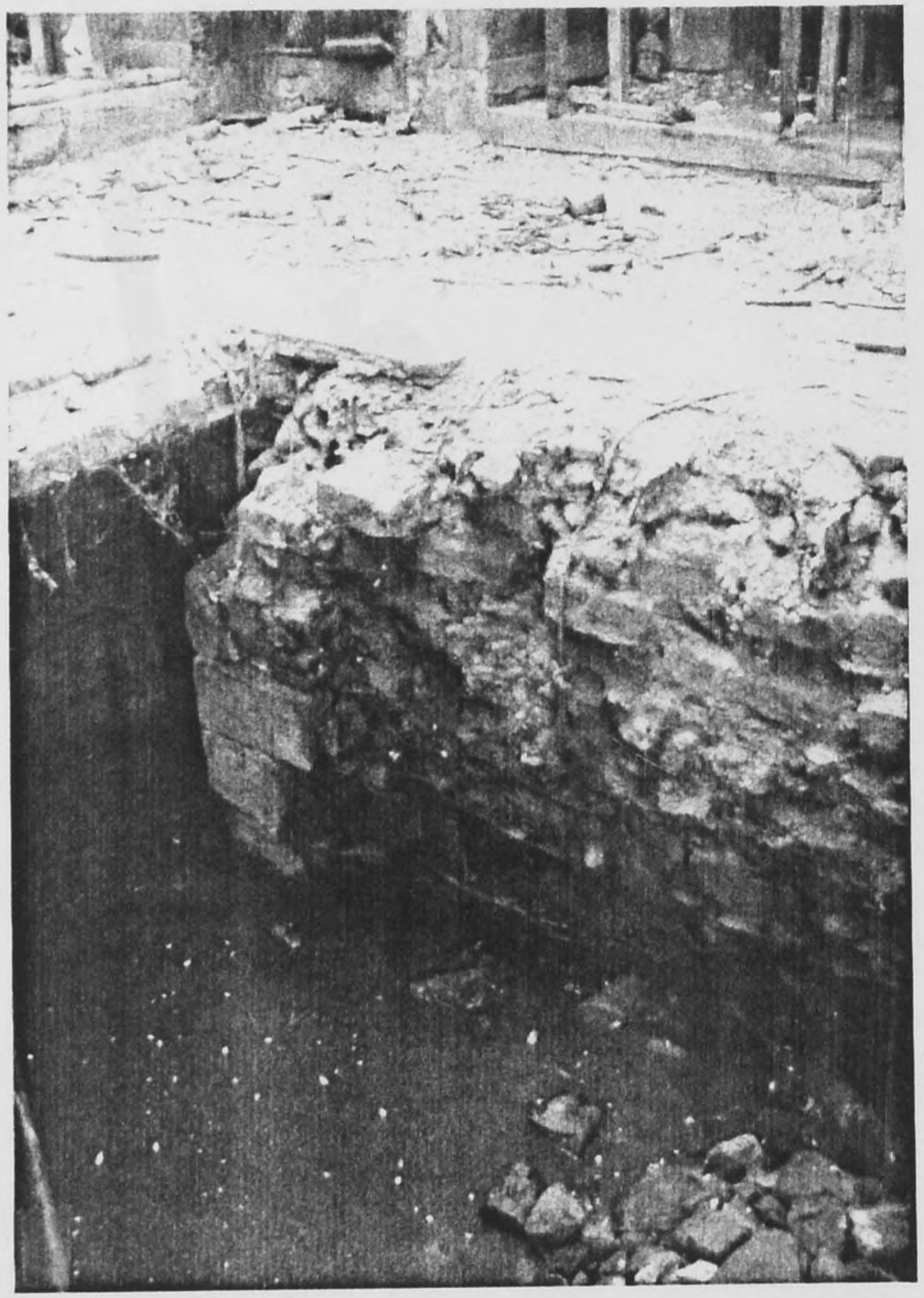


Fig. 18 Groundwater in excavation below Khani Bey Mosque

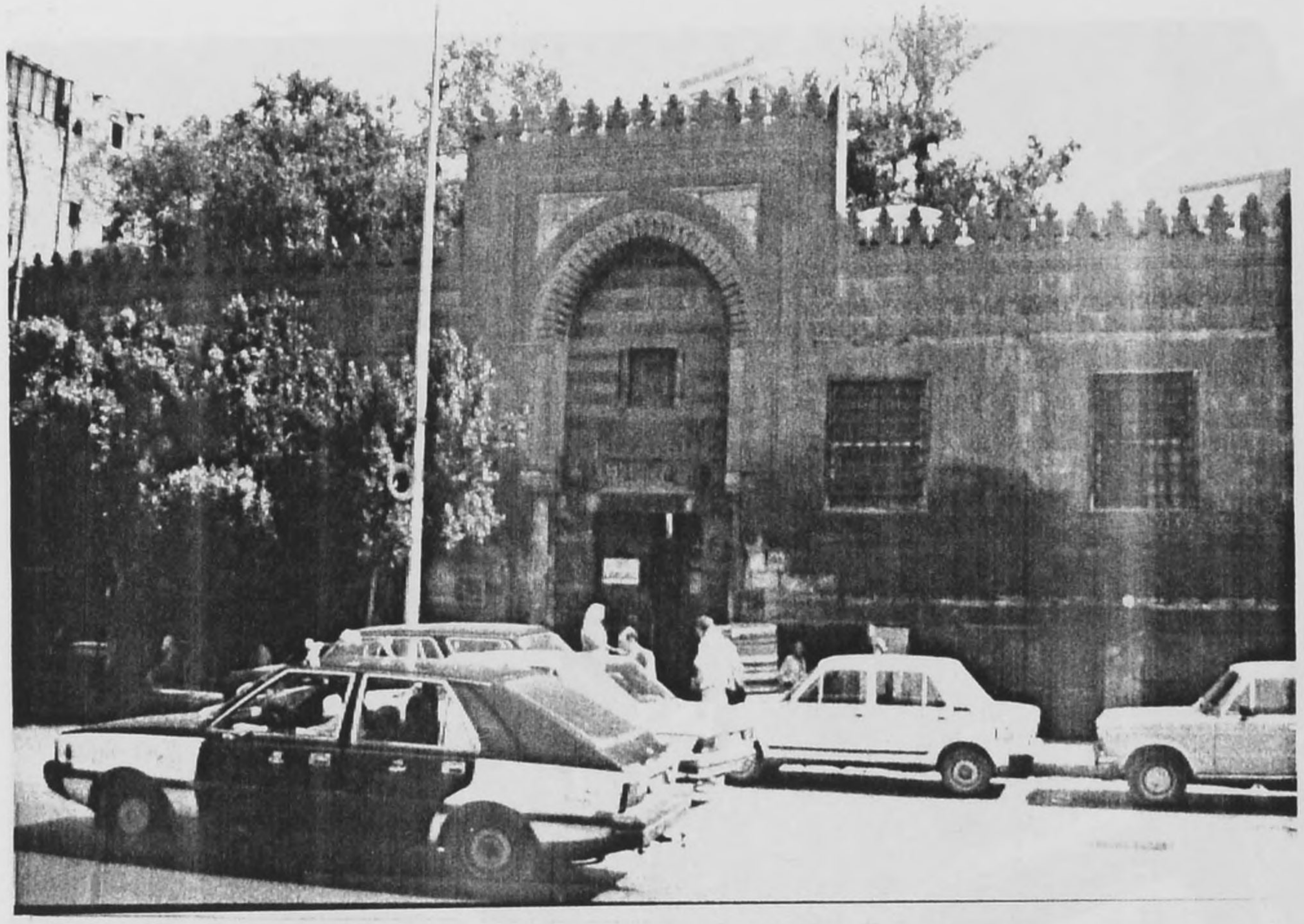


Fig. 19 Front of Sultan Mahmoud Takkayan Preschool

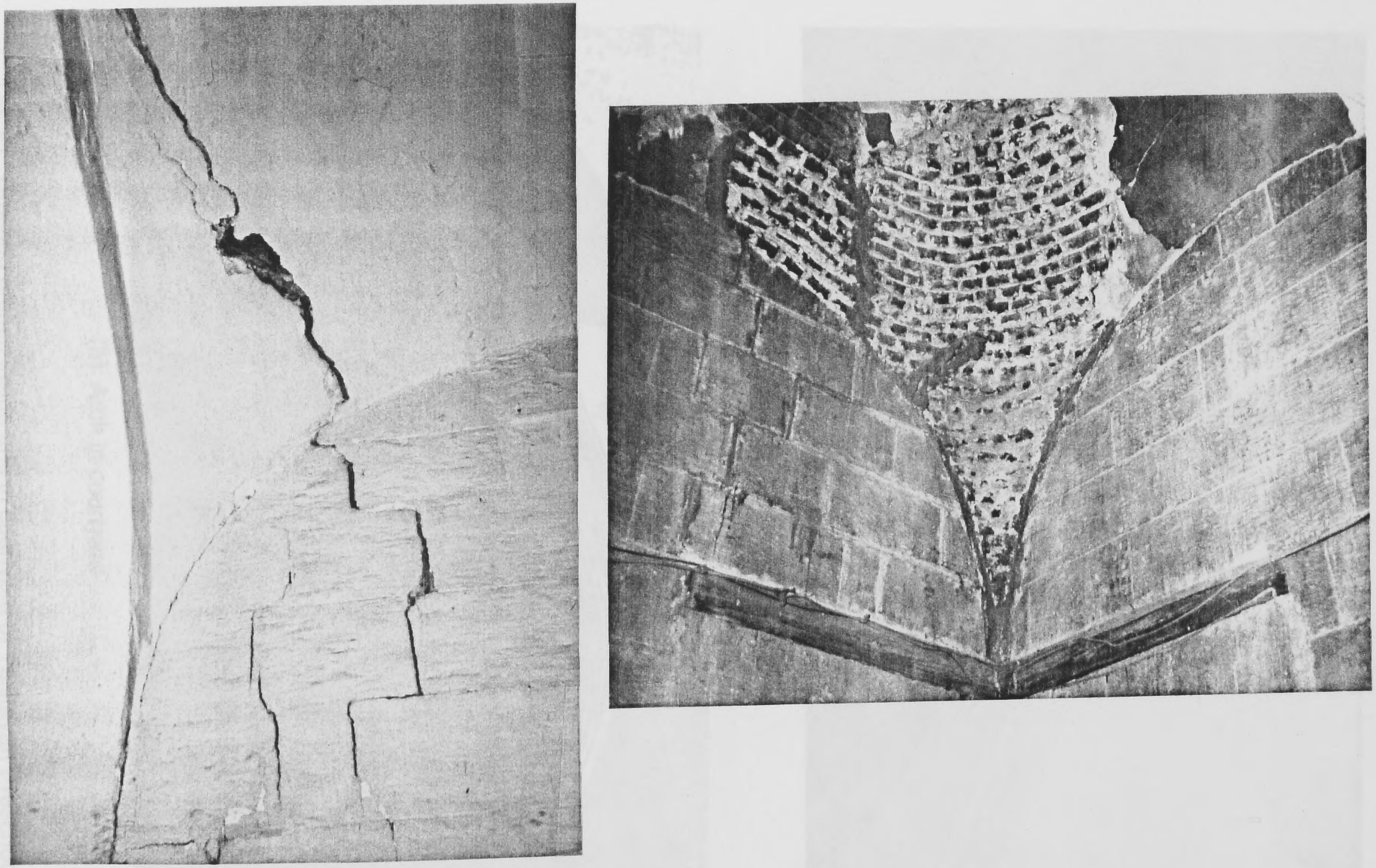
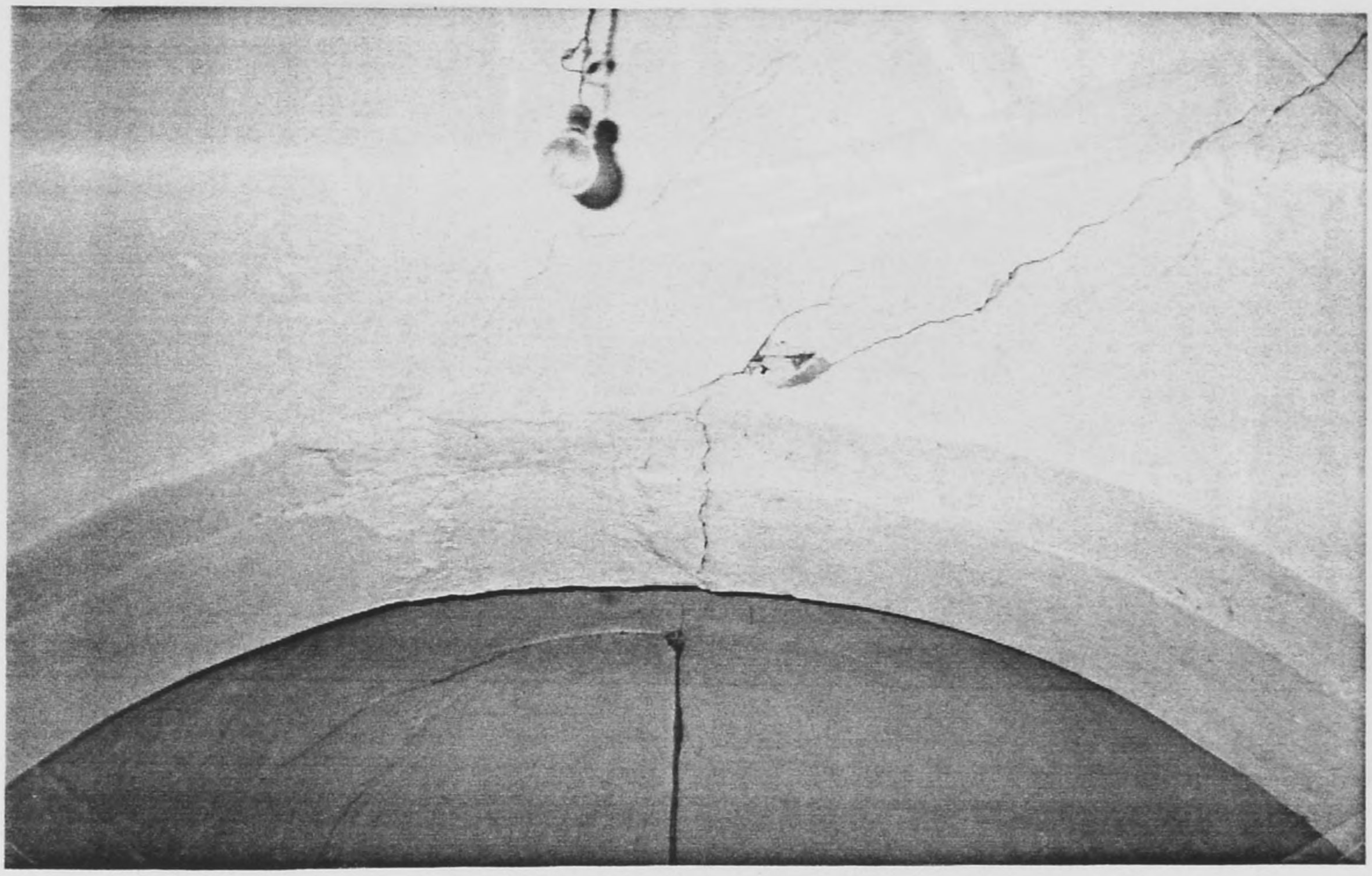
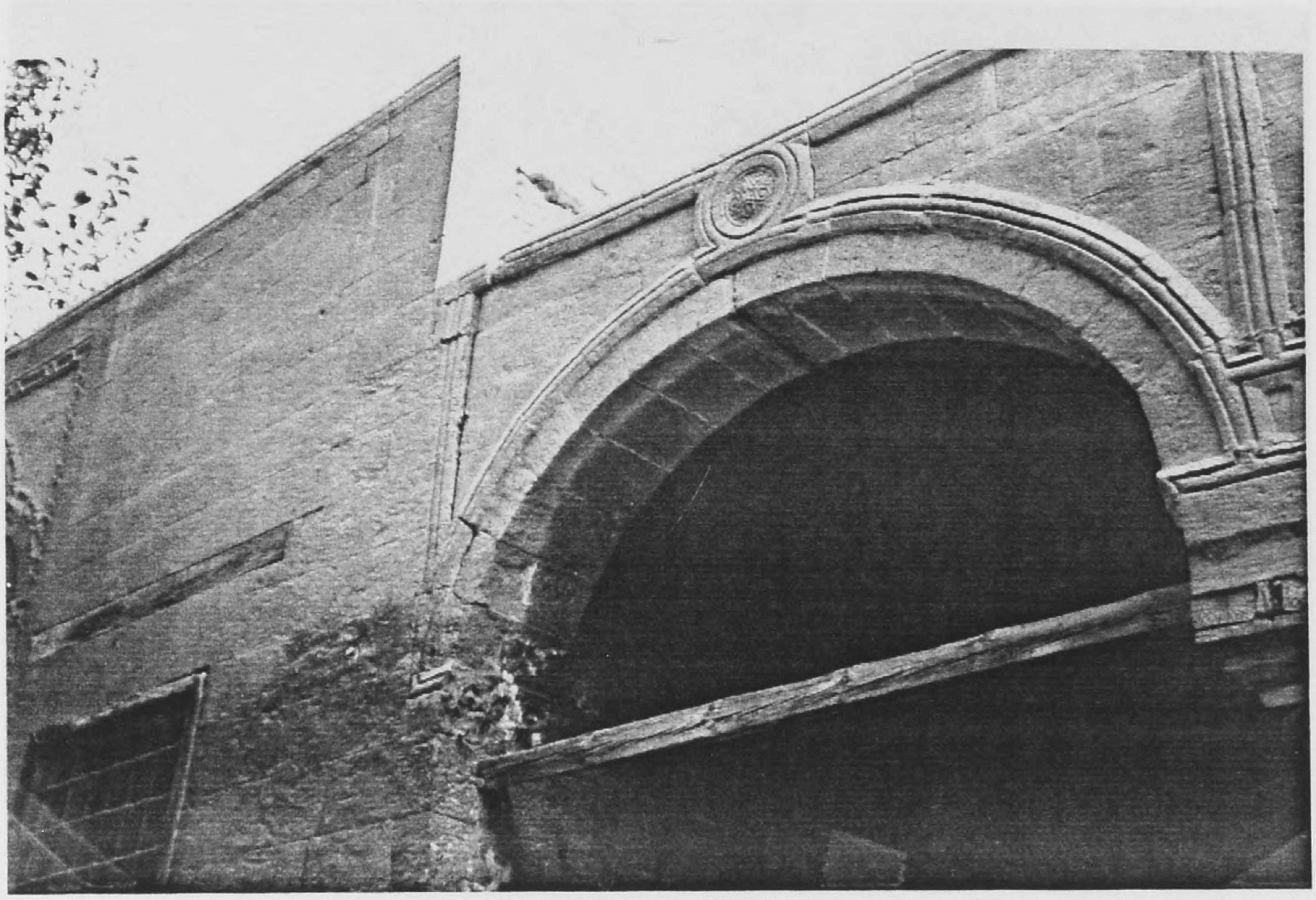


Fig. 20 Cracked and spalled domes inside Takkayah Preschool

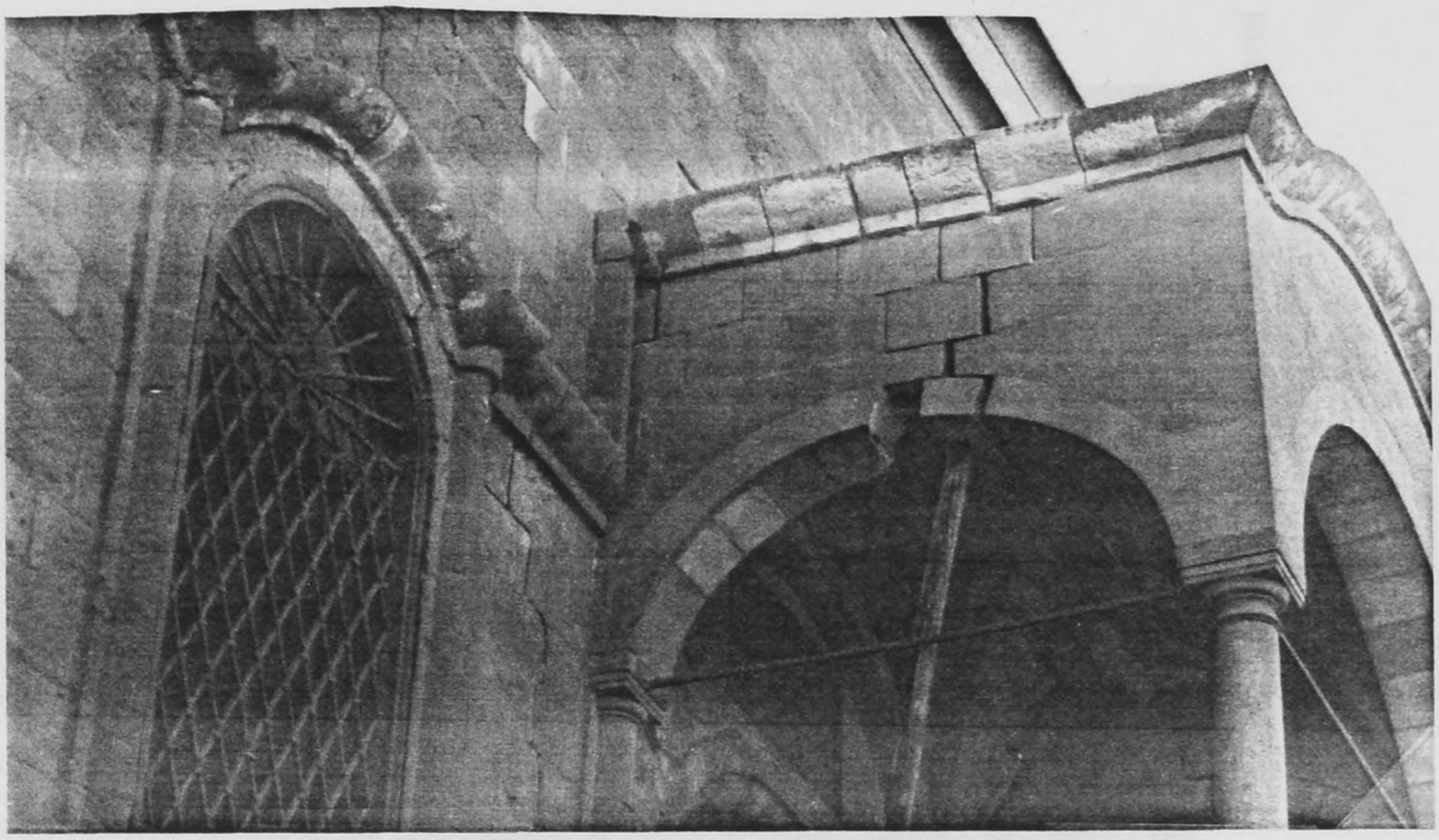


(a) Arch inside preschool

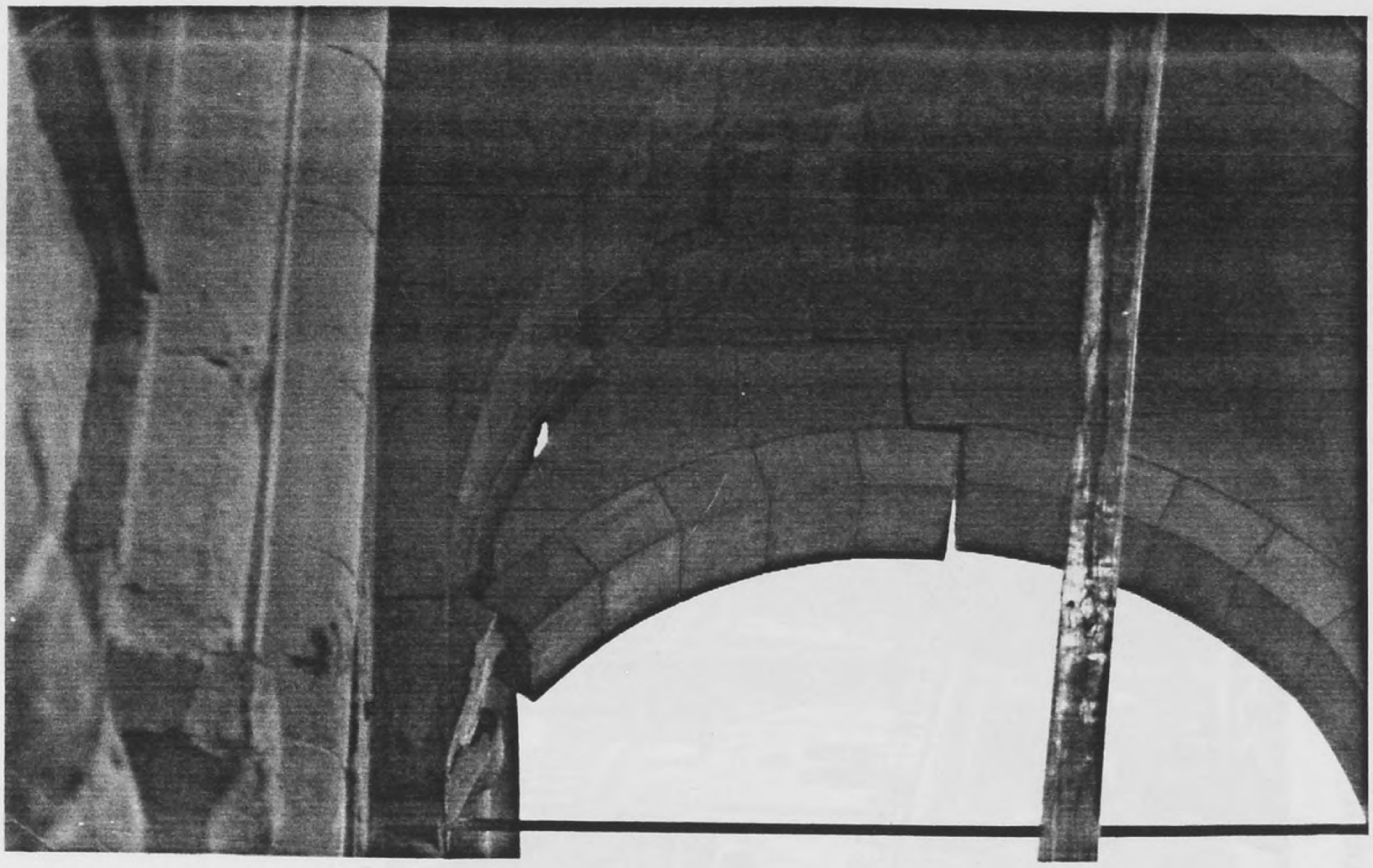


(b) Arch in courtyard

Fig. 21 Cracked arches inside and in courtyard of Takkayah Preschool



(a) Post supporting loose stone in arch



(b) Loose stones in arch

Fig. 22 Porch of courthouse in the Citadel or the Mohammad Ali Mosque

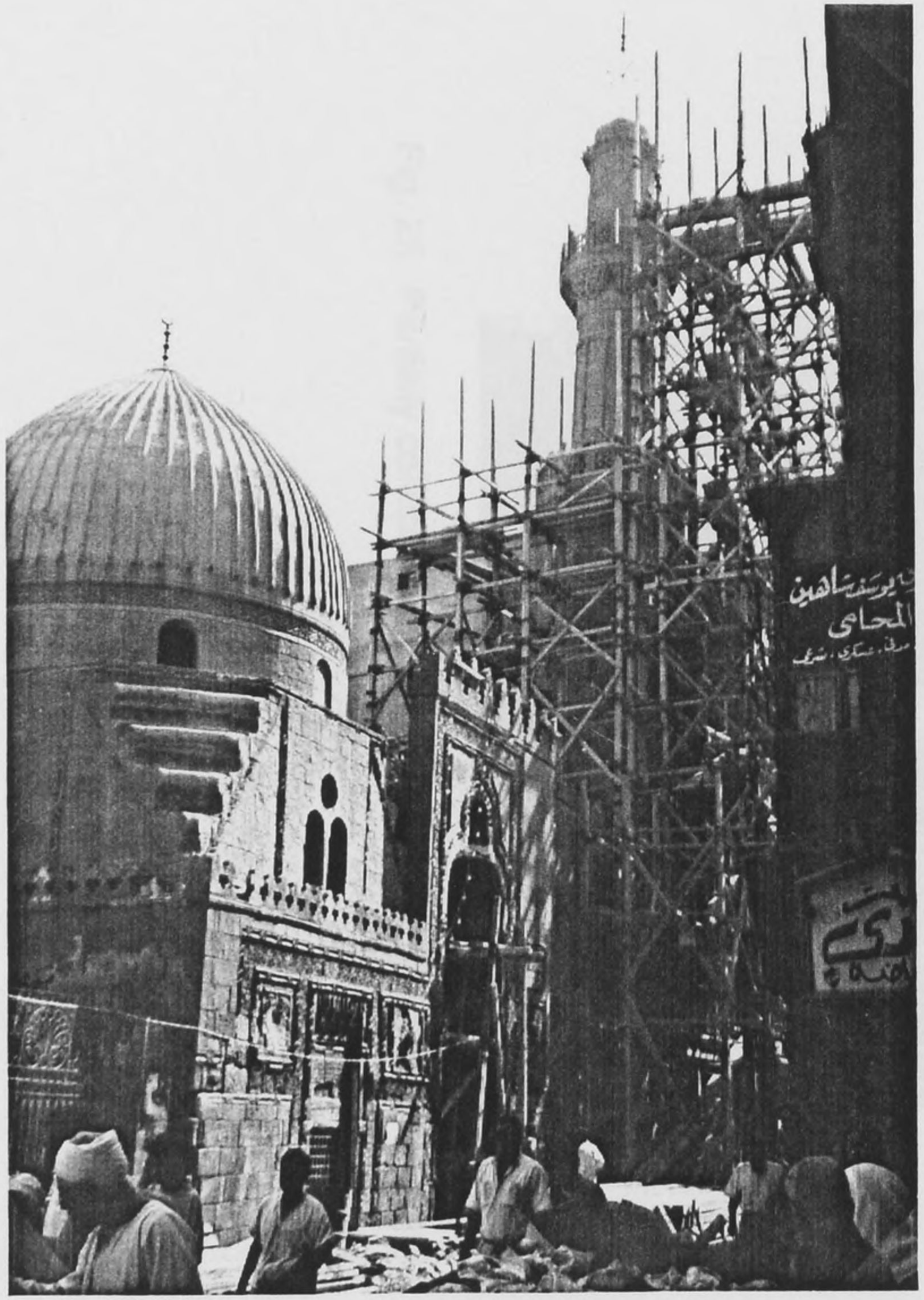


Fig. 23 Leaning minaret tower at Mosque Al-Kadi Yahya

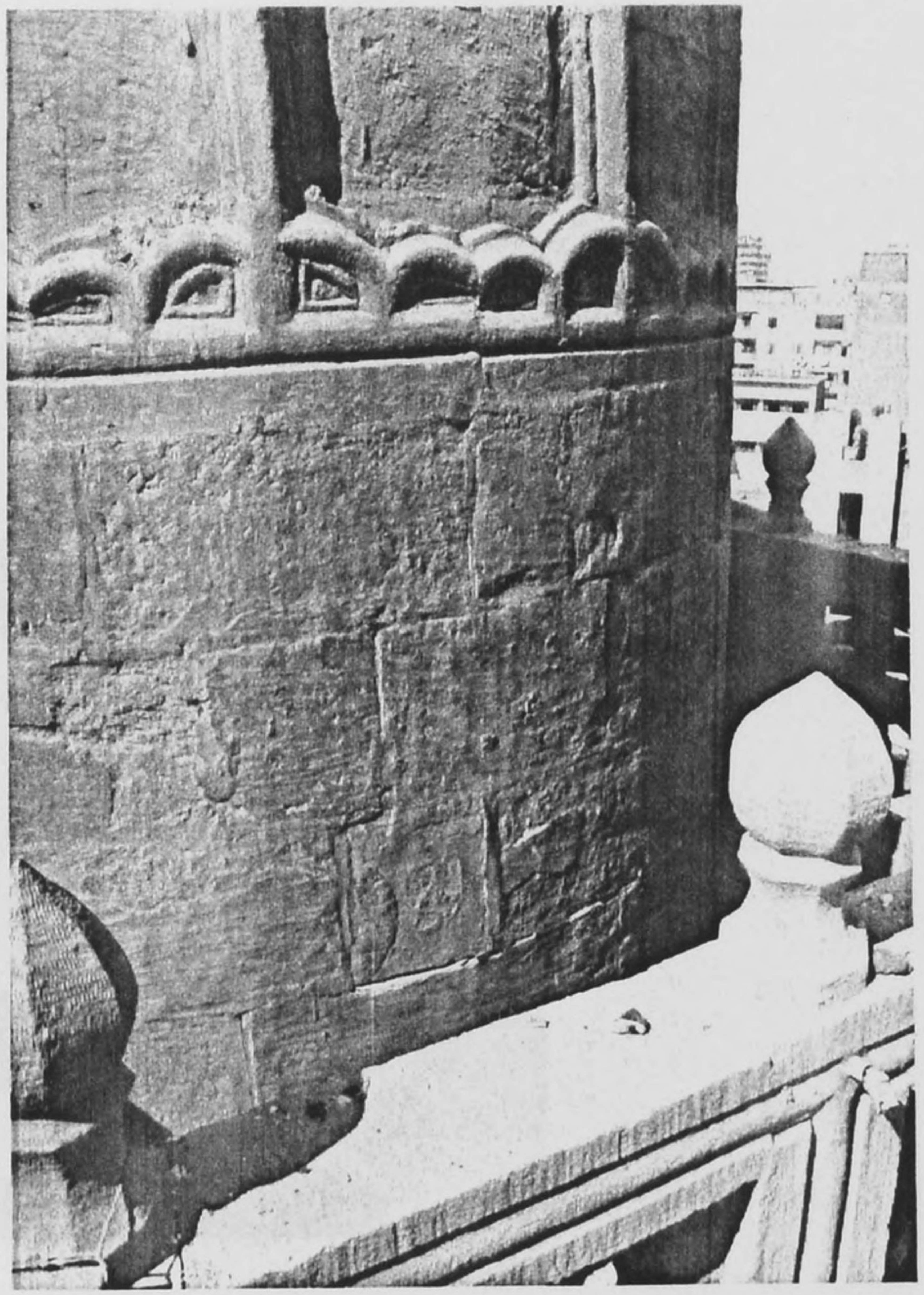


Fig. 24 Cracking and spalling along cracks in minaret tower section above roof of mosque

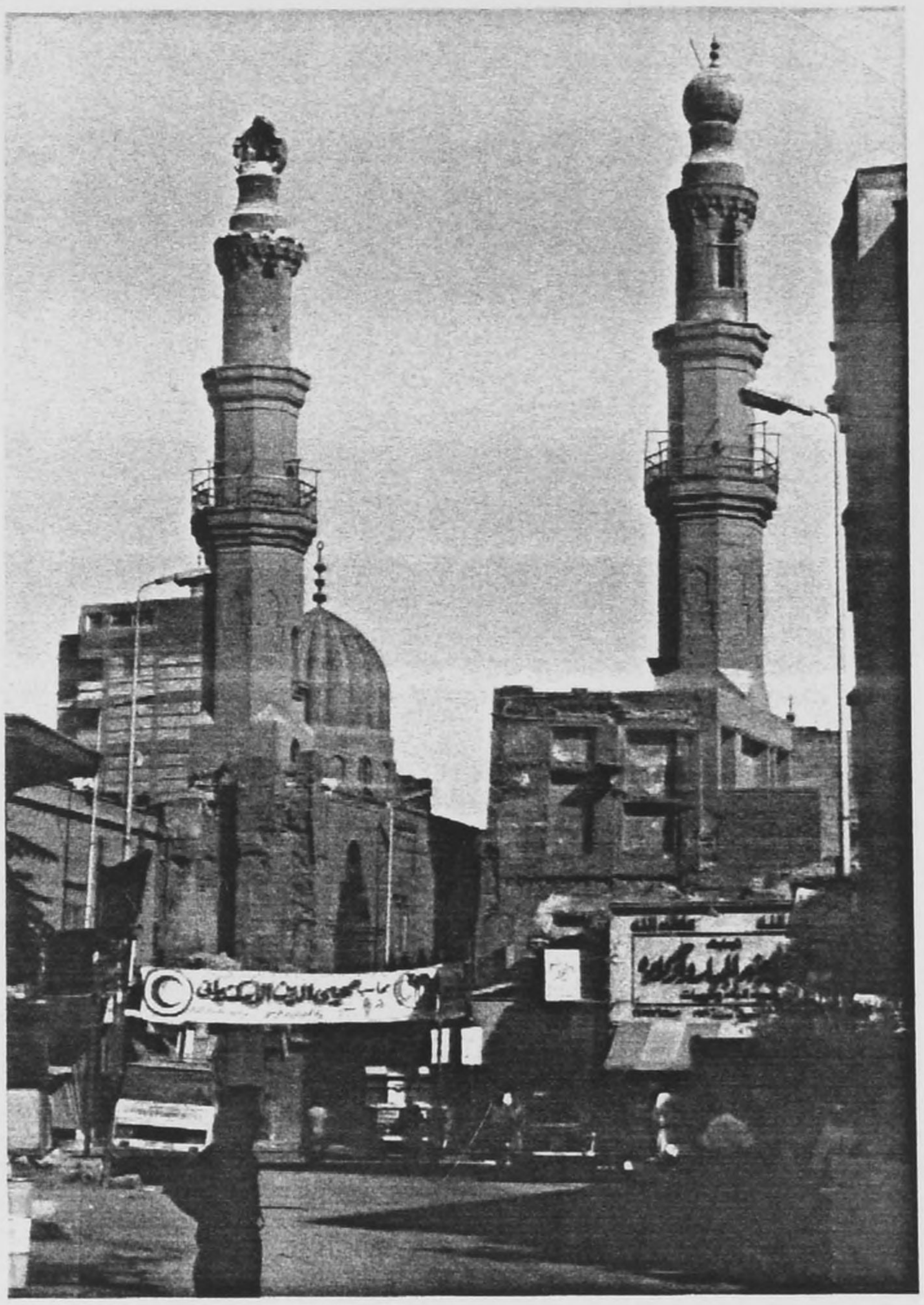


Fig. 25 Partially collapsed top of minaret at Amir Shaykhu Mosque

AIIM SCANNER TEST CHART # 2

Spectra

4 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
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Times Roman

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6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
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Century Schoolbook Bold

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6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
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News Gothic Bold Reversed

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Bodoni Italic

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10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

Greek and Math Symbols

4 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδεξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
6 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδεξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
8 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδεξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
10 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδεξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡

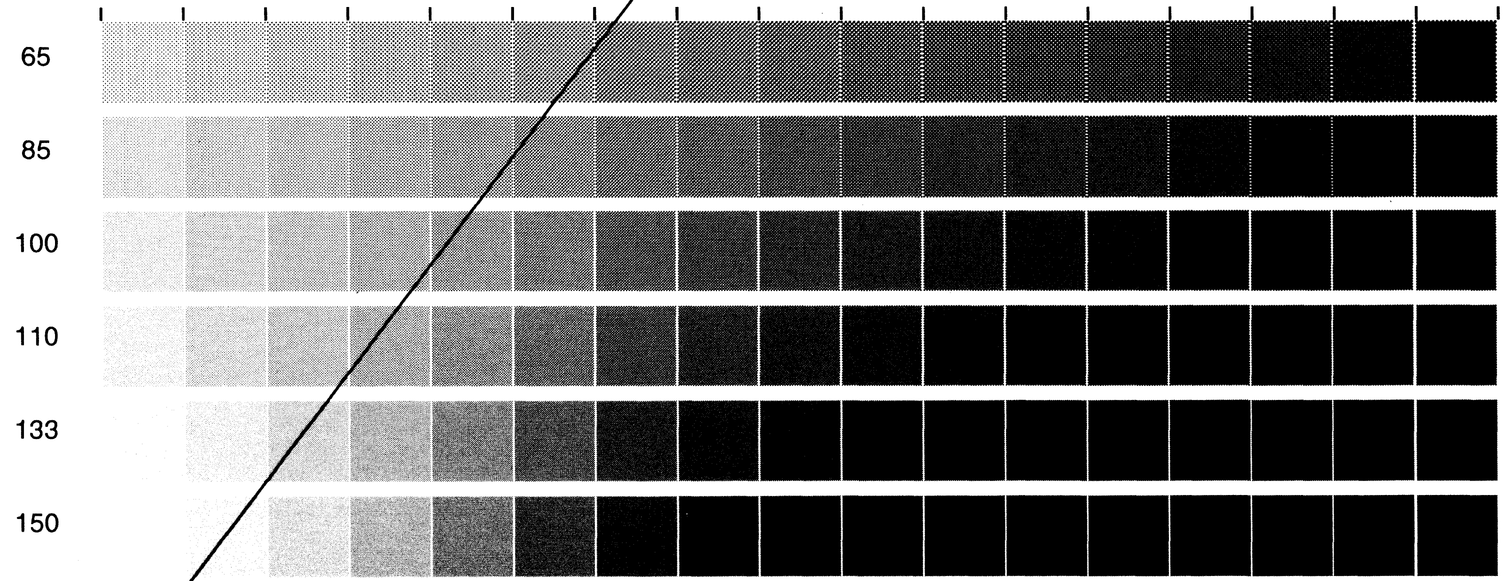
White

Black

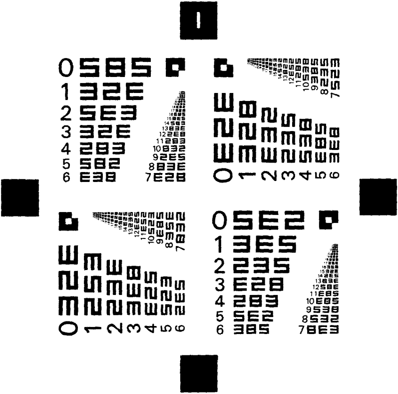
Isolated Characters

e	m	1	2	3	a
4	5	6	7	o	°
8	9	0	h	l	B

MESH HALFTONE WEDGES



RIT ALPHANUMERIC RESOLUTION TEST OBJECT, RT-1-71



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