Petra

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Field leader

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Paleoseismology and archaeoseismology of sites in Aqaba and Petra, Jordan

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*Field guide

Quaternary Geology of Aqaba

Aqaba, Jordan is built predominantly on alluvial fan sediment derived from the adjacent mountain ranges to the east (Fig. 1). The drainage basin of the Wadi Yutim reaches far into the eastern plateau and covers a minimum area of 1100 km^2. It is the largest drainage system in the southern ‘Arabah valley and flows into the 'Ain Defiya depression in Eilat. Several branches of the Wadi Yutim flow southwestward toward the Gulf of Aqaba. The Aqaba Regional Authority has constructed flood control measures to divert runoff away from the city of Aqaba.

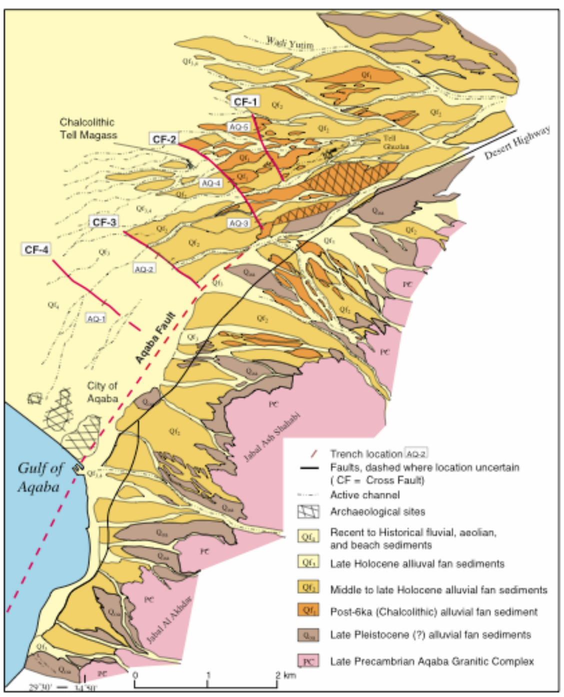

Figure 1. Geologic map of the Aqaba region based on interpretation of 1:25,000 scale airphoto from 1953. Cross fan faults (CF 1-4) are mapped as continuous lines even though these features are eroded by wadi washes. These cross faults formed as normal to oblique-slip faults associated with a left stepover in the Dead Sea Transform. Locations AQ 1-3 mark the sites of exploratory trenches excavated across the NW-trending faults. A high concentration of archaeological ruins in the Aqaba area provide age constraints on surface deformation and provide a unique record of damage from past earthquakes (modified from Niemi and Smith, 1999).

Niemi and Smith (1999) divided the alluvial fan sequence in the Aqaba region into five mappable fan units (Q_{oa}, Qf_1, Qf_2, Qf_3 and Qf_4). Remnants of a Pleistocene alluvial fan sequence, designated Q_{oa}, located near the mountain front, may correlate to the Upper Pleistocene fan surfaces mapped on the Shehoret alluvial fan sequence west side in Israel. The oldest Holocene alluvial fan surface (Qf_1) is distinguished by a moderately developed desert varnish. It overlies archaeological artifacts from the Chalcolithic period (Tell Magass and Tell Ghuzlan) dated to 5-6 ka. The Qf_2 fan surface is slightly inset into or buries the Qf_1 surface. The age of the Qf_2 fan surface is unknown. The young alluvial fan deposits are generally incised across older fan surfaces and include the active channel deposits and distal fan sediments. The youngest unit also contains aeolian and beach sediment within the coastal zone.

Paleoseismology

Airphoto interpretation of the Aqaba regional surficial geology (Fig. 1) suggests that a strike-slip fault emerges from the gulf and that slip is transferred to cross faults. This geometry constrains the location of the Aqaba fault to lie east of the cross faults and west of alluvial fan surfaces that contain no north- to northeast-striking fault lineaments. The location of the Aqaba fault is therefore believed to lie within a 500-m swath that is covered by the modern city (Fig. 1). It appears that the Aqaba fault follows a recent wadi that has obliterated its active fault morphology. A ground-penetrating radar survey in the city confirmed the location of a portion of the Aqaba fault (Slater and Niemi, 2003; Abueladas, 2005; Abueladas *et al.,* in prep).

The Aqaba fault apparently trends northeast with increasing curvature as it dies out toward the northeast. This bending to the northeast of the eastern bounding fault of a pullapart has been noted for other large pullapart basins along the Dead Sea Transform including the Dead Sea and the Sea of Galilee (Garfunkel *et al.*, 1981; Garfunkel, 1981). Reches (1987) showed using clay model experiments that that faults initially bend away from each other at a dilational jog in ductile materials. This geometry led Reches (1987) to conclude that the Arabian plate was thickening by ductile deformation. The Aqaba fault should therefore have a reverse component to its motion. New GPR data across the fault confirm this prediction (Abueladas *et al.,* in prep; Fig. 2).

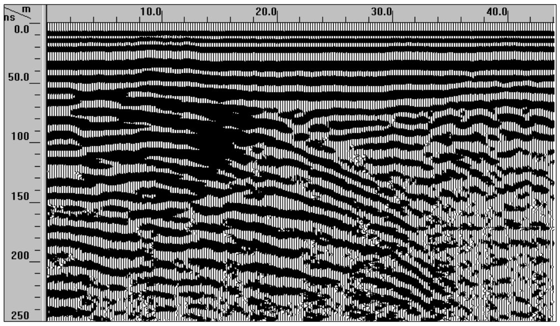

Figure 2. GPR profile highlighting the potential reverse component of the Aqaba fault. These data were collected as part of the MERC project "High resolution marine geophysical imaging of active faults in the Aqaba-Eilat region".

Geological trenches excavated across several faults in Aqaba document that the fault motion is transferred from the Aqaba fault onto five northwest - trending cross-faults that produce active tectonic subsidence at the head of the Gulf (Mansoor, 2002; Slater and Niemi, 2003; Fig. 4). Mapping of alluvial fan and buried soil horizons in trenches excavated on three of the cross faults reveal multiple fault ruptures on the highest scarps and fewer distinct ruptures on the lowest scarp (Mansoor, 2002). The scarp heights range from 25 cm across the youngest Qf_4 surface to 1.3 m across the older Qf_1 and Qf_2 surfaces. These data indicate that scarp heights reflect cumulative slip events. The most recent scarp-forming event fault occurred after A.D. 1045-1278 based on a corrected, calibrated radiocarbon age from charcoal collected from a buried campfire at the base of the scarp (Fig. 3). This likely represents fault motion in either the historical earthquakes of 1212 or 1068.

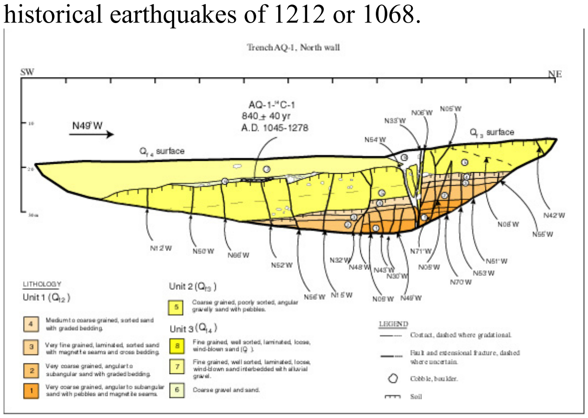

Figure 3. Trench log of the north wall of AQ-1 excvated across the cross fault 4 (Mansoor, 2002).

ARCHAEOSEISMOLOGY IN AQABA

Islamic Ayla

Based both on the historical accounts and the archaeological work of Whitcomb and Parker (*e.g.* 1996), it is clear that earthquakes have played a significant role in the history of the Aqaba region. The exact location of the Aqaba fault remains somewhat uncertain because it has never been exposed in paleoseismic trenches in this heavily urbanization location. Whitcomb (1993; 19) hypothesized that the wadi running across the ancient site of Ayla has its origins in erosion along the structural weakness of the fault itself. Thus, our main objective in investigating the city wall of Ayla was to test this hypothesis and to locate the Aqaba fault.

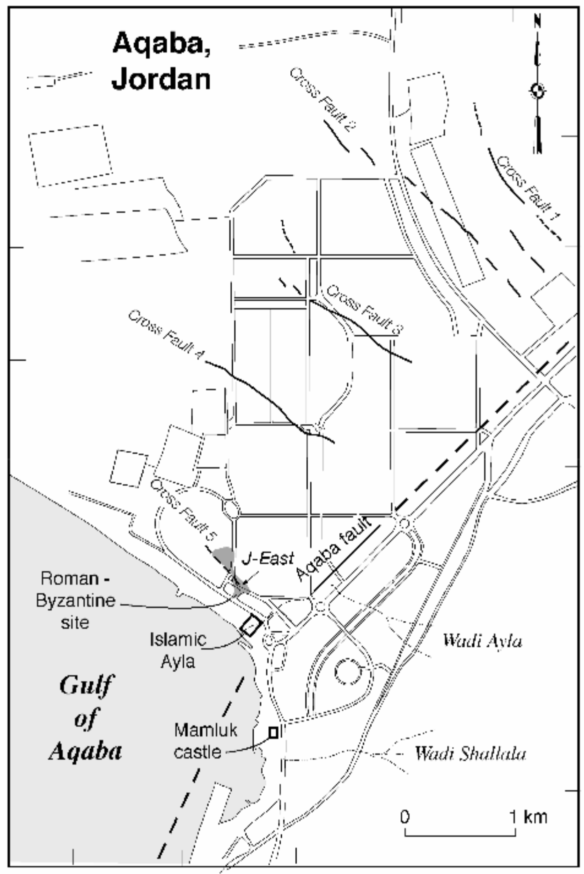

Figure 4. Map of the city of Aqaba showing the location of major archaeological sites. Active cross faults (CF) mapped from aerial photos and discovered in the archaeological excavations of J-east are also shown (Thomas et al., 2007).

The Early Islamic site of Ayla, extensively excavated by Donald Whitcomb of the Oriental Institute at the University of Chicago, is a walled city, circa 250 m southeast of the Byzantine city wall excavated by Parker (1996; 2002), and approximately 850 m north of the Mamluk castle in modern Aqaba (Fig. 4). The city of Islamic Ayla was probably founded under the Caliph ‘Uthman ibn ‘Affan around 650 A.D. (Whitcomb, 1995; 277). The city seems to have suffered some damage as a result of the 748 A.D. earthquake, and extensive reconstruction with the beginning of the Abbasid period (Whitcomb, 1994; 9). It is described by al-Muqaddasi in the late 10th century, as he described it in reference to the ruins nearby of the Roman/Byzantine site (after Whitcomb, 1997; 359). The town was severely damaged by the earthquake in 1068 A.D. (Ambraseys, 1994; 31). The destruction and loss of life (accounts claim that all but 12 residents who had been out fishing were killed) caused by this earthquake may account for the relative ease with which Baldwin I of Jerusalem took over when he arrived with a small retinue in 1116 A.D. Baldwin I constructed a small fortification (the origin of the current castle?), and a new settlement grew up around this (Whitcomb, 1997; 359). The site of Islamic Ayla was apparently never reoccupied to any significant degree after the time of the Crusaders.

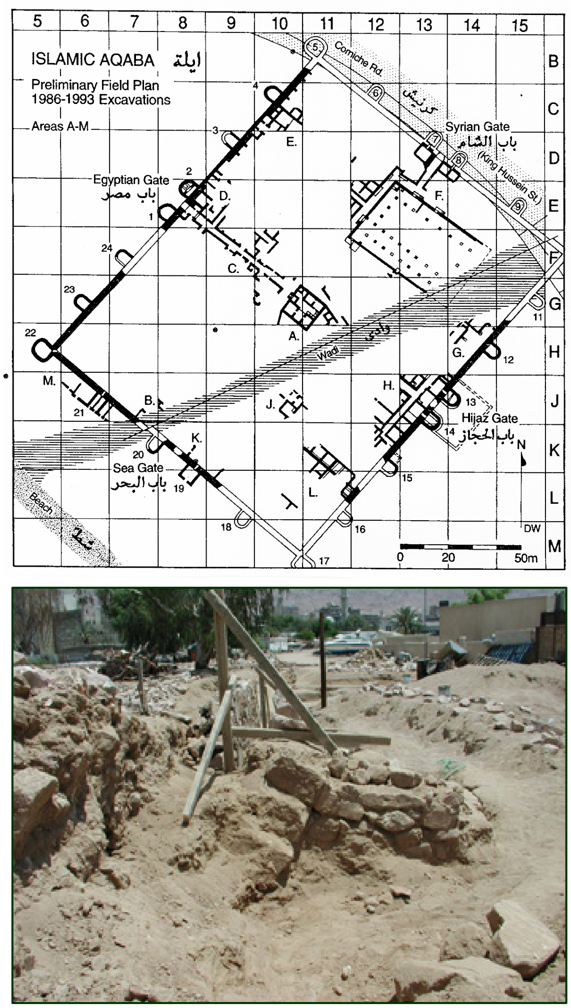

Figure 5. (Top) Site Plan of Early Islamic Ayla, from Whitcomb (1995). (Bottom) Section of the Sea Wall, tilted outward and buttressed in antiquity, with reconstructed wall on original alignment in background, view to SE.

Al-Hamoud and Tal (1998) conducted geotechnical investigations using three boreholes to a depth of 12m on the tell of Islamic Ayla. Archaeological deposits overlie sand and gravels. They noted tilting and sinking of exterior walls that they interpreted as slumping due to horizontal ground acceleration in an earthquake. Similar conclusions were reported by Al-Tarazi and Koryenkov (2007). According to the analyses of Mansoor *et al.* (2004), Ayla lies in an area of high liquefaction susceptibility due to the presence of saturated sands at shallow depth. This means that during seismic shaking, the substrate may lose its ability to bear weight, resulting in collapse of structures. Areas in the city of Aqaba that experienced subsidence in the Nuweiba earthquake of 1995 lie along the beach zone near the ancient site of Ayla (Wust 1997; Malkawi *et al.,* 1999; Al-Tarazi, 2000).

Rucker and Niemi (2005) reported on the results of excavation of the northeast corener tower the walled citadel of Islamic Ayla. In the four trenches excavated, the wall aligns across the entire width of the wadi indicating that no fault offset is present in the NE or SE city wall or through the corner tower in the wadi. Furthermore, the 2001 Department of Antiquities restoration project in the south corner of the site revealed a section of the Sea Wall that was tilted outward (Fig. 5). The outer edge of this section before excavation would have appeared on the ground surface 1.5 to 2m from the alignment of its actual foundation. Interestingly, it appeared to have been buttressed and continued in use in antiquity. This phenomenon, (easily caused by liquefaction and subsidence, not faulting) may provide an explanation for the apparent misalignment in the Sea wall above foundation levels observed by Whitcomb and others.

Byzantine Aila

The Roman Aqaba Project directed by S. Thomas Parker (North Carolina State University) excavated a monumental mudbrick structure heavily damaged by successive earthquake faulting in Aqaba (in excavation Area J-East), between 1994 and 2003. A collaborative study of the excavated evidence from this area identified a sequence of seven earthquakes that have ruptured the fault since the 2nd Century A.D. (Thomas *et al.,* 2007).

Previous excavations of the monumental Byzantine mudbrick structure indicate that a portion of this building collapsed in the earthquake of May 19, 363 A.D. This date is derived from over 100 coins of Constantius II (337-361 A.D.) found beneath a thick layer of collapsed mudbrick walls. Our detailed mapping of the excavated Early Byzantine walls revealed ancient repair work over seismically-induced structural wall failures. The structural repairs of the Church walls indicate that the southwest corner of the building subsided. This damage may have occurred in a minor earthquake (perhaps a significant foreshock) prior to the major earthquake that collapsed the structure. Based on subsidence across the fault location, changes in floor elevations, and layers of collapsed mudbrick, the archaeological data suggest that the site was ruptured in an early 2nd Century earthquake, an early 4th Century earthquake, and the 363 A.D. earthquake. The monumental use of the structure was converted to domestic use in the late 4th to early 5th Century.

Figure 6. Faults across the Byzantine mudbrick building in Aqaba. Person is standing by the wall that is faulted. View toward the SW.

We also have evidence for primary ground rupture for at least four post-date 363 A.D. earthquakes that transect the ruins in the J-East area of Aila. Primary fault rupture is documented in stratigraphic sections and plan maps of walls of various construction age (Fig. 6). Two earthquakes occurred during the Late Byzantine to Umayyad period (sith to eighth Century). There is a hiatus of deposition at this location between the Umayyad and the modern age. The two most recent earthquakes, with 42 and 35 cm of dip slip, occurred some time after the 8th Century and may correlate to the historical earthquakes of 1068 and 1212 A.D. No stratified materials were found at this site that could be used to further refine the timing. Our data suggest significant periods of active seismicity (M 6-7) in the 4th, 7th-8th, and probably in the 11th-13th Centuries. These data clearly show that historical earthquake catalogues are incomplete with regard to some of the less damaging earthquakes that have affected southern Jordan but may have played a significant role in the cultural history of the region. The data also document a long period of quiescence since the last phase of intense earthquake activity along the southern Dead Sea transform and highlight the elevated potential earthquake hazard in the region.

GEOLOGY FROM AQABA TO PETRA

The mountains east of Aqaba and for a distance of 50 km northeast are Precambrian igneous rocks of the Aqaba Granite Complex (Rashdan, 1988). These igneous rocks are composed of granite, monzogranite, granodiorite, and quartz diorite that developed during the Pan-Arrican orogeny. A series of dikes with widely varying compositions from diabase to felsite cross cut the granitic rocks.

Nonconformably overlying the Aqaba Granite Complex are Paleozoic rocks of the Ram Group (Fig. 7). Cambrian arkosic sandstones and conglomerates derived from the weathered granitic rocks (Salib Formation) form the basal unit. These rocks grade into massive quartzose sandstones of Cambrian to Silurian age (Umm Ishrin and Disi Formations). Outcrops of Lower Paleozoic sandstone are present 50 km northeast of Aqaba along the eastern mountain range. Erosion of the sandstone supplies the sand which has formed extensive dune field within Wadi ‘Arabah to the north.

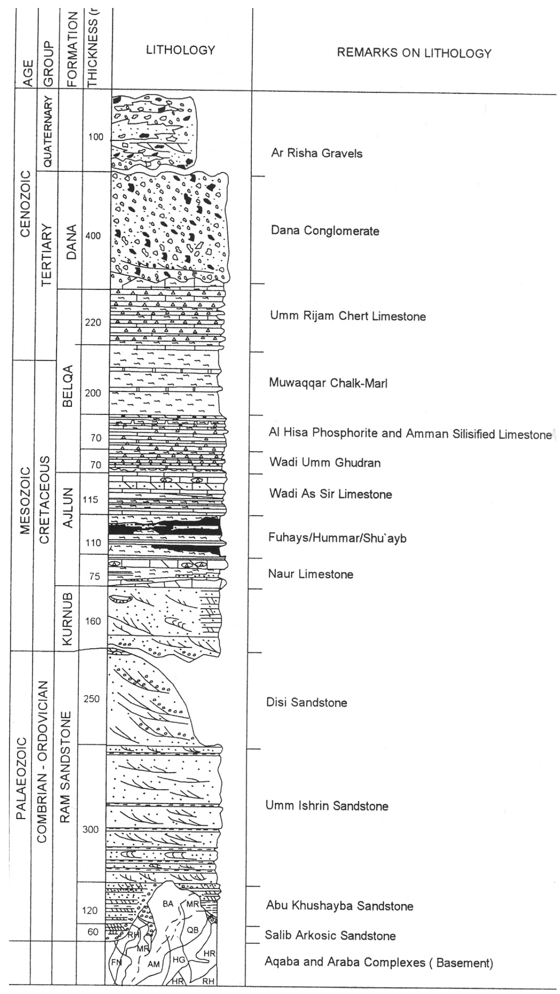

Figure 7. Generalized graphic log of the lithostratigraphic units exposed in Southern Jordan (Barjous, 2003).

The road to Amman crosses the Aqaba Complex rocks within the canyon of Wadi Yutim along part of the King's Highway—the *Via Nova Traiana* commissioned by Trajan in 111-114 A.D. The walls of the canyon expose the cross-cutting late phases of dike intrusion during the latest Precambrian. Pleistocene terraces line the course of the wadi.

Near the turn-off for Wadi Rum, the valley opens and the contact between the Aqaba Complex and overlying sedimentary sequence is easily discerned. The nonconformity represents an erosional peneplain that is tilted to the east (Abed *et al.,* 1998).

North of Wadi Rum the region of Ras En Naqab is a spectacular area of scenic beauty. The NW-SE trending fault escarpment separates Lower Cretaceous varicolored sandstone and Upper Cretaceous carbonates in the north from the sandstone highlands in the south (Abed *et al.,* 1998). The recent highway improvements in this area expose outcrops of faulted bedrock.

PETRA

Petra, the "Rose City" was the capital of the Nabataeans during the Hellenistic and into the Roman periods. In the Siq of the Petra, you will first pass through the white Disi Sandstone and then the underlying thick red Umm Ishrin sandstone into which most of the monuments were carved (Abed *et al*., 1998). "Following the course of Wadi Musa, the city-center was laid out on either side of the colonnaded street on an elongated plan between the theater in the east and Qasr al Bint in the west. Petra basin boasts over 800 individual monuments that were mostly carved in the Cambrian sandstone by the technical and artistic genius of the Nabataeans" (Barjous, 2003). Some of the most famous antiquities at Petra include al Khazneh (the Treasury), Qasr al-Bint (the free-standing, two-storey building), the Roman Amphitheater, the Great Temple, the Temple of the Winged Lion, and the Petra Church.

Several earthquakes are likely to have caused damage at Petra since it's founding. Josephus Flavius in his *Jewish Wars* describes an earthquake in 31 B.C. that "killed an infinite number of cattle and thirty thousand people" in Palestine (Guidoboni, 1994: 173). Evidence from this early occupation period is scanty because of later monumental construction.

There is evidence of massive destruction in Petra at the Temple of the Winged Lions, at the Great Temple, and other monuments dated to the beginning of the 2nd century A.D. Much scholarly debate has focused on the interpretation of the destruction in light of sparse and rather enigmatic documentary evidence for the Trajanic annexation of Nabataea ca. 106 A.D. The lack of historical text leaves open the possibility of multiple interpretations for the destruction horizons. Coins and milestones suggest Arabia was "acquired" rather than gained by military force. Corroborating evidence for a 2nd C. earthquake in the southern Levant has been documented at Nabataean sites in the Negev, Wadi 'Arabah (Arava Valley), and at Aqaba. The coincidence of an earthquake with a documented political transition makes unequivocal interpretation of the archaeological record extremely difficult (Niemi *et al.,* 2006).

Undeniably, Petra sustained significant damage in the May 19, 363 earthquake that affected the region from north of Lake Tiberias to Aqaba in the south. Russell (1980) and Guidoboni (1994: 264-267) provide convincing literary data for the earthquake. Furthermore, coins from 358-361 beneath collapse at the Petra site of Ez-Zantur (Stucky *et al.,* 1990) and Aqaba (Parker, 1999) confirm damage at both sites in the earthquake.

Figure 8. Collapsed columns of the Great Temple at Petra viewed toward the east. The collapse likely dates to late antiquity sometime after the 6th century.

In the Byzantine period, the Urn tomb was modified into a 5th century church. Other churches were constructed through the 6th and 7th centuries as Petra thrived as a Byzantine center. Many Hellenistic- and Roman-era Nabataean building stones and architectural elements are reused in this construction phase. Excavators of the Petra garden and pool complex just east of the Great Temple (Bedal *et al.,* 2007) note that the final destruction there probably occurred in the 6th century, perhaps they hypothesized, by the 551 A.D. However, the source rupture of this earthquake is the Lebanese coast (Elias *et al.,* 2007).

Scrolls found in the Petra Church provide an unprecedented record of Late Byzantine Petra (Feima *et al.,* 2001). The church was destroyed in a fire at the end of the 6th or the beginning of the 7th century. The fire carbonized scrolls that were being stored in the church. The last recorded date on the scrolls is 597 A.D. It is possible that the earthquake that destroyed

Aereopolis (east of the Dead Sea) based on a dedicatory inscription found there that states “Restored in 492 (597-598 C.E.) after the earthquake” (Zayadine, 1971), also caused damage in Petra.

After the fire and into the 7th century A.D., the church ceased to function as an ecclesiastical building, materials were gutted, and the shell of the structure was converted to a domestic complex. Feima *et al.* (2001) noted evidence for two earthquakes in the later phases of the Petra Church—one in the 7th Century and one in the medieval to Ottoman period—at which time no columns remained standing.

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