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EARLY APPLICATIONS OF DOMICAL VAULT IN JORDAN
ヨルダンにおける初期のドーム状ヴォールト

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The present paper aims to report early applications of the domical vaults on a square plan supported by four arches and spherical-triangle pendentives, which remain in Levant of Roman Empire. They are made of cut stones, and the technique of which traces back to Hellenistic tradition. New measurements confirm that these domical vaults with pendentives form a hemisphere. They were probably constructed in the second century AD. A shallow dome made of cut stone voussoir was adequate to create a geometrical form, but it was considerably inapplicable to a monument more than 10 m in diameter. This method was a tentative solution before the pendentive dome was innovated in the second half of the sixth century AD.

Keywords: *domical vault, pendentive, Roman architecture, Levant, building technique, digital measurement technique*
ドーム状ヴォールト , ペンデンティブ , ローマ建築 , レバント , 建設技術 , デジタル計測技術

1. Introduction

1-1. Purpose of the study

Much has been written about the nature of the pendentive (German *Hängezwickel*, French, *pendentif en triangle sphérique* or *calotte sur pendetifs*) and about its general development.[1)] The method of a shallow dome on a square plan supported by four arches and spherical-triangle corners, or pendentives (Fig. 1, No. 2) in Roman architecture of Levant was already mentioned in the end of the nineteenth century.[2)] In 1939, Hamilton, who made an architectural study of the Pagan Tomb at Samaria, reported its shallow dome and spherical-triangle corners, and briefly discussed similar examples of ancient Levant.[3)] Forty years later, Creswell reported there were many examples in Levant, including Nuweijis near Amman, West Baths at Jerash, Pagan Tomb at Samaria, Brad, and Golden Gate of Jersalem (Table 1).[4)] Recently, the Baths at Petra is nominated as one of the earliest candidates of this kind of dome.[5)] These knowledge might lead to a consensus that the geometrical principle of the hemisphere domical vault with spherical-triangle corners were already known among Roman builders in Levant. Nevertheless, actual form and building technique of these candidates have not been clarified, probably because it was not easy to measure upper structure of them.[6)] In addition, this kind of technique has never been counted among scholars of Roman building techniques.[7)] Under this circumstance, the author had an opportunity to make a general survey in ancient Levant.[8)] Based on its results and previous researches, a list of the candidates of domical vault is prepared (Table 1). In order to clarify their details, the author focused on the earlier candidates in Jordan, including Baths at Petra, Nuweijis near Amman and West Baths at Jerash, all of them are dated between first and second century AD. From 2011 to 2012, the author made some fieldwork in collaboration with Department of Antiquity in Jordan.[9)] A 3D laser scanner was used to measure the upper structures.[10)] The present paper, thus, aims to report and examine these early applications of domical vault with pendentive.

1-2. Terminology

As mentioned above, an example of a shallow dome on spherical-triangle corners of Roman architecture was already reported by Choisy. “In Jerash, the connection between the square plan and spherical cap (dome) is obtained by pendentive whose shape is spherical triangle,” and he called it as “spherical vault (voûtes sphériques).”[11)] Judging from his axonometric drawing, the monument of Jerash is supposed to be North Tetrapylon, which does not exist anymore as it was, and was reconstructed in 1980s. Unfortunately, Choisy did not say clearly if it was a shallow dome, sphere of which was the same as the one of spherical-triangle corners, or it was a hemisphere dome rests on four spherical-triangle corners, i.e., pendentive dome.[12)]

Choisy’s understanding of pendentive was revised by Jackson. He explained the geometrical principle of pendentive dome as follows. “*ABCD* (Fig. 1) is the square and the *inscribed* circle *E* the dome to be placed over it. Imagine a larger dome *FGHI* circumscribed about the square. Then if the four segments *ABG*, *BCH* and the other two are cut off vertically on the lines *AB*, *BC*, etc., we get the imperfect dome shown by Fig. 1, No. 2.” Then, “the great invention of Byzantines was to slice off the top of this imperfect dome on a plane level with the crown of the four spherical triangles on which the dome rests are the pendentives, the strength of which lies in their being arched in two directions both horizontally and vertically, and they are supported by being wedged in between the four arches of the square (Fig. 1, No. 4).”[13)] In this way, Jackson had strictly distinguished between the first type of dome (shallow dome on pendentives) and the second type of dome (pendentive dome). Jackson correctly pointed out that the second type of dome, or pendentive dome was

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Table 1 List of domical vault with pendentive in Levant

Monument	Element	Material	Construction date	Restoration	Country
Baths at Petra	pendentive, domical vault	cut stone	second half of the 1st century (pottery and ornamentation)	partly repaired (1968-69	Jordan
Nuwaijis near Amman	arch, pendentive, domical vault	cut stone	middle of the 2nd century (architectural ornamentation)	partly repaired (?)	Jordan
West Baths at Jerash	arch, pendentive, domical vault	cut stone	second half of the 2nd century (architectural ornamentation)	original	Jordan
North Tetrapylon at Jerash	arch, pendentive, domical vault	cut stone	second half of the 2nd century ?	reconstructed (1981-83)	Jordan
Pagan Tomb at Samaria	arch, pendentive, domical vault	cut stone	beginning of the 3rd century (style of sarcophagi)	original ?	Israel
Underground Tomb at Gadara	arch, pendentive, domical vault	cut stone	beginning of the 3rd century ?	original	Jordan
Brad	pendentive, domical vault	cut stone	later than 4th century (architectural style?)	original ?	Syria
Golden Gate of Jersalem	arch, pendentive, domical vault	cut stone	between 616 and 629? (historical context)	original	Israel
Double Gate of Jersalem	arch, pendentive, domical vault	cut stone	same to Golden Gate?	original	Israel

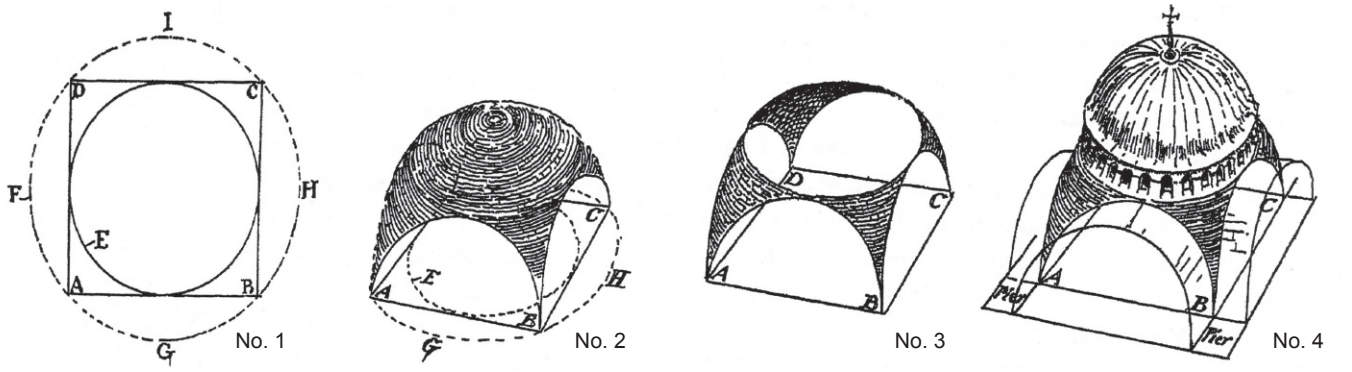

Fig. 1 Principle of domical vault with pendentive (No. 2), and of pendentive dome (No. 4)

an invention of the Byzantine architecture. Nevertheless, he probably did not know enough that the fist type of dome (shallow dome on pendentives) had already appeared in Levant before Byzantine time. "In Syria, however, they never arrived at this method…"[14)]

Creswell reported many examples of the first type of dome (shallow dome on pendentives) of Levant. Creswell did not accept the term 'imperfect dome' of Jackson, because Jackson focused on only the second type of dome, and restated it as follows; "…we get **a shallow dome on spherical-triangle pendentives** as shown in (Fig. 1, No. 2)."[15)] Creswell made it clear that the distinction between these two types of domes in no way affects the nature of pendentives, and this opinion was totally accepted by Mango.[16)] Even so, it is not convenient if we call both types of domes as 'pendentive dome'. With this, Mango called the first type of dome as 'domical vault,' and the second type of dome as 'pendentive dome.' According to Mango, "the difference between the two is that whereas in the domical vault the pendentives and the calotte form a continuous spherical surface, this is not the case in the dome, which is built on the smaller radius than that of the pendentives beneath it."[17)] It might be correct that a dome is kind of vault as Sear says: "A dome is a vault of segmental or semicircular section erected upon a circular base," and he called our shallow dome as 'sail vault.'[18)]

In order to avoid confusion, thus, the author follows the manner of Mango. That is, the first type of dome, which is the target of the present paper, is the **domical vault**, and not the dome which rests on spherical-triangle pendentives. Most examples of it are known in Levant of Roman time, and they are made of cut stone voussoir. Outside of Levant, there are only two known examples; Mausoleum of Galla Placidia at Ravenna and many parts of Agia Sophia at Constantinople.[19)] The second type of dome is **pendentive dome**, which appeared in Byzaintine architecture.

2. Baths at Petra

2-1. Architectural remains

Baths at Petra[20)] is located in the city center, west of the Great Temple and south of the Temenos Gate. The building consists of three chambers; a circular one, a square one and a square one for a large staircase. All parts of the building are underground, and only a staircase chamber can be seen from the ground. They are constructed of rose local sandstone in ashlar masonry. Some stuccos remain on the surface of the inner walls.

The circular chamber (diam. 5.15 m) has been cleared, revealing a stone pavement (Fig. 2, left). Eight half columns (dim. 0.30 m) with Corinthian capitals and Attic-type bases are attached to the inner wall. Above the capitals there is a groove for an inset entablature.[21)] Many pieces of plaster mouldings including an astragal, ovolo with painted egg and tongue, dentils, cyma reversa, corona with a drip cornice, beveled ovolo, and sima, were found on the ground and in the fill.[22)] Every two bays have a semicircular niche, at the tops of which were traces of a conch.[23)] The roof consists of an intact dome of stone blocks with a circular window at the top; however, there are no pendentives. Some parts of roof are probably restored.

Next to the circular chamber, there is a square chamber (4.64 x 4.61 m), which can be entered through the south wall of the circular chamber (Fig. 2, right). It has also been cleared to the floor level. The roof consists of an intact domical vault of cut stone voussoir with a circular window on the top (Fig. 3).[24)] There are four spherical-triangles with five courses on the corners.[25)] However, there are no arches with voussoir on the four sides as Rababeh reported. In addition, when the chamber was excavated in 1968, a part of the upper structure and south wall (?) had been collapsed (Fig. 4).[26)] In fact, new

blocks can be observed on the north and south parts of the domical vault and the north and west walls. Moreover, there is no arch made of voussoir on the four wall as Rababeh drew. Based on this fact, therefore, the following measurements (2-2.) must be treated as an estimation.

2-2. Measurements

The domical vault and its four corners was measured by a 3D laser scanner (Fig. 5). Its measuring data is as follows: There are eight point-clouds and ca. 226 million points were measured. Spheres and targets registration is in accuracy of 2.3 mm best to 3.8 mm worst cloud to cloud. ICP Registration is less than 2.2 mm accuracy cloud to cloud. The original point was placed on a local topographical point.

Based on the measurements, a theoretical sphere was calculated by commercial software, the surface of which fits the actual measured points of the domical vault with minimum error (Table 2). Before calculating the data, the measurements of restored parts were carefully excluded. As a result, the radius of the domical vault was 3.84 m (standard deviation 0.031 m) and the radius of the pendentives was 3.53 m (standard deviation 0.032 m). Since the radius of hemisphere standing on the square room is estimated as ca. 3.55 m, the domical vault was probably close to a hemisphere, but the pendentive would not have been so. In addition, the center of domical vault is ca. 29 cm lower than the center of hemisphere, thus, the top of the domical vault is ca. 0.4 cm lower than the hemisphere (Fig. 24). A section was drawn based on the point-cloud image and sketches (Fig. 6).

2-3. Construction date

Since no inscriptions from the Baths have been discovered and no archaeological findings have been reported, only the stylistic analysis of the architectural ornamentation can be used for the dating. McKenzie categorized the floral from the Baths capitals as Group A, which includes those from the Kasr el Bint and from the Temple of the Winged Lions.[27] McKenzie concluded that the Baths were possibly constructed slightly later than the Kasr el Bint (the beginning of the first century AD) but not as late as the Temple of the Winged Lions; that is, at the end of the first century AD. The early date for the Baths at Petra is surprising, but it is acceptable here because the structure is not so established as those of Nuweijis near Amman and of the West Baths at Jerash.

3. Nuweijis near Amman

3-1. Architectural remains

Qasr an Nuweijis (Nuweijis) is located about 4 km north from the city center (Fig. 7). The monument stands beside the big cross-road of beltlines and neighbors the restoration center of the Department of Antiquity. Qusayr an-Nuweijis means ‘palace of the princes.’[28] Nuweijis was first discovered by T. Black and photographed by Mantell. It was also visited by Conder, who made the first publication of this monument.[29] Creswell reports with good photographs and discusses the spherical-triangle pendentive;[30] however, no architectural report has appeared yet.

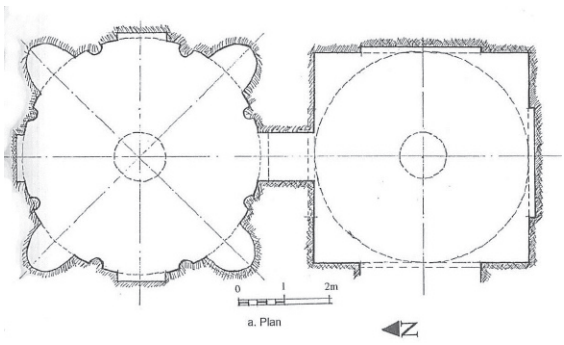

Fig. 2 Petra, section of the Baths

Fig. 3 Petra, domical vault with pendentive of the Baths

Fig. 4 Petra, pendentive during the excavations

Fig. 5 Petra, point-cloud image of the Baths, section looking from the west to the east

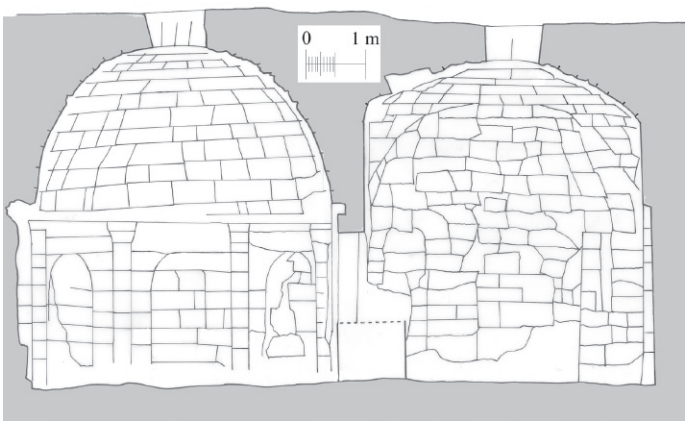

Fig. 6 Petra, Baths, section looking from the west to the east

The monument is a square of about 12.3 m, with a small chamber in each corner (Fig. 8). In the center of the plan, two semi-circle vaults cross and support a domical vault. There are four spherical-triangles with six courses on which the domical vault rests (Fig. 9). Massive outer walls, measuring ca. 1.2 m, are decorated by pilasters in corners and in middle of each walls, which project out a few centimeters. Ionic capitals crown the top. They support a continuous entablature, which is decorated with architectural ornamentations. The architrave has three fasciae and a crown moulding with the section of cyma recta on top. The frieze ornamentation is vegetables and figures on the façade (southeast), and palm leaves on the other sides. The geison is decorated by, from the bottom to the top, an egg and dart taenia on the bottom, small dentils, a small modillion, and sima with acanthus leaves. There are a high continuous attic and parapet still remaining, which stand along the entablature and hide the central domical vault from people looking up from the ground.

Large limestone is used in all parts of the building, which mostly remain in good condition. The upper structure of four chambers and part of outer walls

Fig. 7 Amman, general view of Nuweijis

Fig. 9 Amman, domical vault with pendentives of Nuweijis, looking from the northwest to the southeast

Fig. 10 Amman, point-cloud image of Nuweijis, section looking from the southeast to the northwest

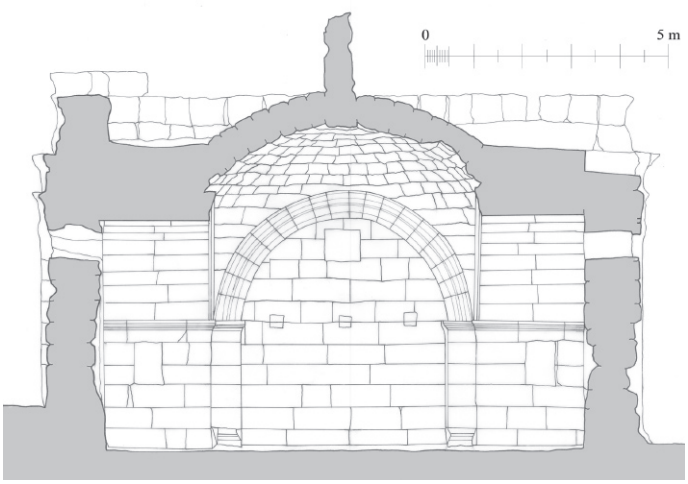

Fig. 11 Amman, Nuweijis, section looking from the southeast to the northwest

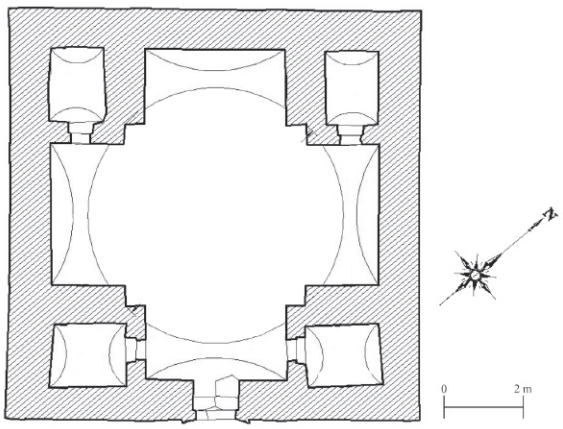

Fig. 8 Amman, plan of Nuweijis

Fig. 12 Amman, the entablature on the south corner of Nuweijis

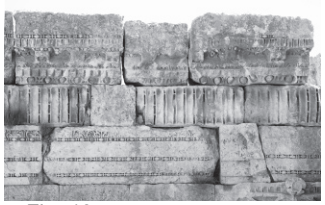

Fig. 13 Jerash, the entablature and geison of the west facade of the west Propylaeum of Artemision

Fig. 14 Amman, the entablature of the Roman Temple

Fig. 15 Amman, the geison of the Roman Temple

have been restored by modern technique. Probably these parts were damaged by an earthquake, but it is not clear when this restoration was made and who did it. The domical vault and pendentive are doubtless original, because there is no restoration on the upper surface of the domical vault. Some stuccos remain on the surface of the domical vault. Thus, there is no hindrance to our study. The wall of the Nuweijis has a width of ca. 60 cm, which is the same width as the tunnel volutes. Four chamber rooms have a small window each, which is supposed to be an entrance to place a gravestone.

3-2. Measurements

The spherical-triangle pendentive at Nuweijis was measured by 3D Laser scanner (Fig. 10). Its measuring data is as follows: There were 29 point-clouds and ca. 1 billion points. Spheres and targets registration is in accuracy of 0.9 mm best to 4.3 mm worst cloud to cloud. ICP Registration is less than 2 mm accuracy cloud to cloud. The original point was placed on a local topographical point.

Based on the measurements, a theoretical sphere was calculated by commercial software, the surface of which fits the actual measured points of the domical vault with minimum error (Table 2). The radius of the domical vault is 4.04 m (standard deviation 0.008 m) and the radius of the pendentives is 3.76 m (standard deviation 0.014 m). Thus, each of the domical vault and the pendentives is created as a hemisphere with high accuracy. Since the radius of hemisphere standing on the square room is estimated as ca. 3.77 m, the pendentive is close to the hemisphere, but the domical vault is bigger than the hemisphere. Thus, the sphere of domical vault is slightly bigger than one of pendentives. In addition, the top of the domical vault is ca. 5 cm lower than the hemisphere (Fig. 25). A section was drawn based on the point-cloud image (Fig. 11).

3-3. Construction date

The monument has been standing above ground probably from ancient time, so was never a target of excavation for archaeologists. In this case, a chronological analysis of the architectural ornamentation might be suitable. The frieze is decorated with a vegetable and figural motif on the front side, and with palm motifs on other three sides. The lower part of the geison is ornamented with an egg and dart taenia on the lowest part, dentils and a lesbian cyma with a heart-shaped leaf. The upper part is decorated with a small modillion, the bottom of which is covered by an acanthus leaf, taenia (?) with palm motif and reed and astragal on top of it, and the crown moulding of cyma recta with leaf motif (Fig. 12). These ornamental motifs and their combinations are found elsewhere in the architecture of the Roman East.

Conder, who reported Nuweijis in the end of the nineteenth century, assigned it to the second century AD without any clear evidence.[31] Rivoira accepted this estimate of the second century AD., but he probably did not know the interior of the Nuweijis at that time.[32] Creswell used the frieze ornamentation, the so-called 'continuous triglyph' (palm leaf which can be seen on the southwest, northwest and northeast sides of the monument) to confirm the construction date of the Nuweijis. According to simple comparison with the frieze ornamentation from the temple of Bacchus at Baalbek, which was begun in the middle of the second century AD., Creswell concluded that the Nuweijis could be dated to the last half of the second century AD.[33] Indeed, the frieze ornamentation of palm motif and the combination of decorations at the geison is almost the same as at Nuweijis.[34] The frieze with palm leaf can also be seen on the west façade of the West Propylaeum of the Temple of Artemis at Jerash, which is dated to AD 150 by the inscription (Fig. 13).[35]

The combination of the architectural ornamentation of the entablature, including the vegetable and figural motif of the frieze, also can confirm the construction date. The entablature from the Roman Temple at Amman has a similar ornamental motif to that of Nuweijis (Figs. 14, 15).[36] It must be noted that the palm motif of under part of the sima and the vegetable motif of the frieze from the Roman Temple are the same as the ornamentation of Nuweijis.[37] The Roman Temple at Amman is securely dated to the time when Geminius Marcianos was the governor of Provincia Arabia (AD 161 - 166).[38] These similar examples, which are located close to the Nuweijis, confirm that the architectural ornamentation of Nuweijis was common in east Palestine around the second century AD. Summing up, the construction date of Nuweijis is around the middle of the second century AD, and not later than the third century AD.

4. West Baths at Jerash

4-1. Architectural remains

The West Baths are located in the north part of the city, which consists of the Cardo and the North Decumanus.[39] The West Baths stand at the east end of the North Decumanus, but do not abut on the colonnaded street. They are located on a terrace somewhat lower than the Cardo. The upper structures have collapsed on the ground, but the plane surface is not obscure (Fig. 16). The West Baths have two main halls with wings on the north and south sides. The entrances of the building are in the two wings (E), which are far from the Cardo. The large hall (F), which is probably a *frigidarium* (cool pool), is divided into three parts by huge arches supporting the upper structure. Three chambers beside the *frigidarium* (A) may have been used as *apodyteria*. Three doorways at the west wall of the *frigidarium* lead to the next hall (C), which is presumed to have once been covered by a great domical vault supported by pendentives. A rising of the pendentive still remains. The heating flutes in the walls clearly indicate that this hall was a *caldarium*. The chambers of the two wings are framed by four great piers, which are joined by arches supporting domical vaults set on spherical-triangles with six courses (Figs. 17, 20). The domical vault in the north chamber, which was firstly reported by Kraeling in 1938, has been preserved mostly in perfect condition.[40] It is not clear what the function of these two winged chambers may have been.

4-2. Measurements

The spherical-triangle pendentive of the West Baths at Jerash was measured by 3D Laser scanner (Fig. 18). The measuring data is as follows: There are

15 point-clouds and ca. 452 million points were measured. Spheres and targets registration is in accuracy of 1.2 mm best to 6.2 mm worst cloud to cloud. ICP Registration is less than 2.5 mm accuracy cloud to cloud. The original point was placed on a local topographical point.

Based on the measurement, a theoretical sphere was calculated by commercial software, the surface of which fits the actual measured points of the domical vault with minimum error (Table 2). The radius of the domical vault is 4.93 m (standard deviation 0.027 m) and of pendentive is 5.79 m (standard deviation 0.017 m). Thus, each of the domical vault and the pendentives is created as a hemisphere with high accuracy. Since the radius of hemisphere standing on the square room is estimated as ca. 5.19 m, the domical vault is smaller than the hemisphere, but the pendentive is bigger than the hemisphere. Thus, the sphere of domical vault is slightly smaller than one of pendentives. In addition, the center of the domical vault is ca. 29 cm higher than the center of the hemisphere, and the top of the domical vault is ca. 3 cm higher than the hemisphere (Fig. 26). A section was drawn based on the point-cloud image (Fig. 19).

4-3. Construction date

Since the city of Jerash was abandoned by the seventh century AD and was not destroyed by modern activities, it is not surprising if the domical vault and pendentives remain as in situ; however, the construction date of West Baths has been discussed for long time because no direct evidence has been

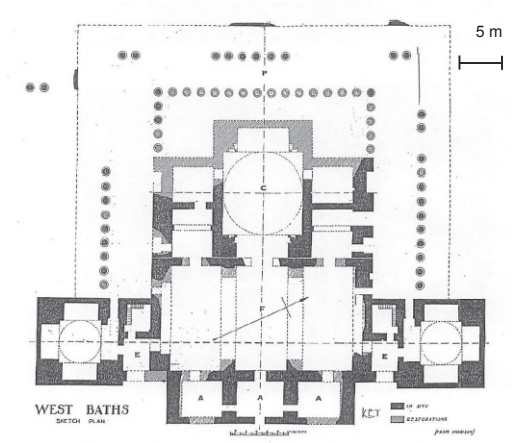

Fig. 16 Jerash, plan of West Baths

Fig. 17 Jerash, domical vault with pendentives of West Baths, looking from the south to the north

Fig. 18 Jerash, point-cloud image of West Baths, section looking from the west to the east

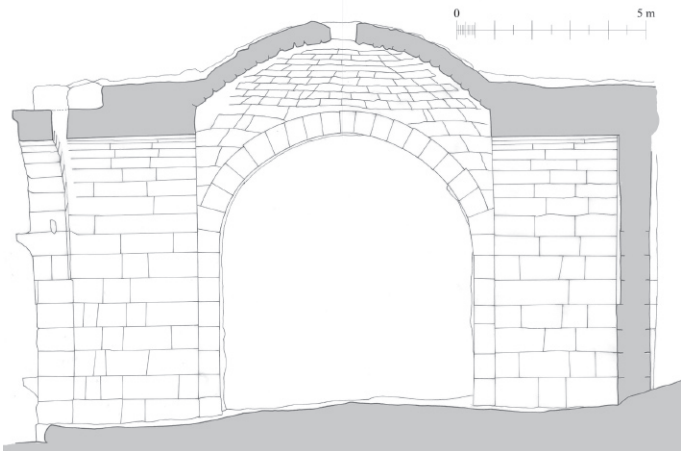

Fig. 19 Jerash, West Baths, section looking from the west to the east

Fig. 20 Jerash, spherical-triangle pendentive of West Baths, northeast corner

Fig. 21 Jerash, Corinthian capital of West Baths

Fig. 22 Jerash, Corinthian capital of South Cardo, near North Tetrapylon

Fig. 23 Jerash, Corinthian capital of North Plaza

Table 2 Measurements of three monuments in Jordan

Petra	X (m)	Y (m)	Z (m)	Radius (m)	N. of Points	StdDev (m)
Domical vault	502.158	-4.848	900.364	3.836	107,099	0.031
Pendentives	502.180	-4.776	900.747	3.526	35,756	0.032
Domical vault and pendentives	502.040	-4.982	900.652	3.552	135,331	0.037

Nuweijis	X (m)	Y (m)	Z (m)	Radius (m)	N. of Points	StdDev (m)
Domical vault	516.655	11.907	1.772	4.037	2,554	0.008
Pendentives	516.561	12.001	2.109	3.763	14,936	0.014
Domical vault and pendentives	516.601	11.964	2.093	3.765	232,778	0.047

Jerash	X (m)	Y (m)	Z (m)	Radius (m)	N. of Points	StdDev (m)
Domical vault	700.894	-753.585	1.198	4.931	248,738	0.027
Pendentives	700.881	-753.658	0.122	5.793	46,677	0.017
Domical vault and pendentives	700.902	-753.594	0.910	5.188	325,790	0.040

Original point is following in the local topographical point of each sites.

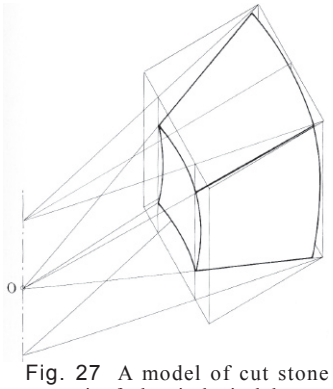

Fig. 27 A model of cut stone voussoir of a hemispherical dome.

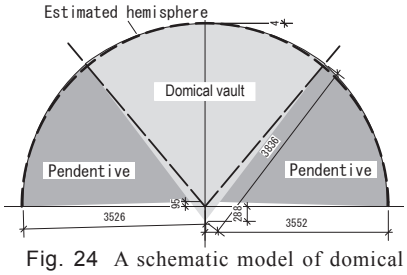

Fig. 24 A schematic model of domical vault of Baths at Petra

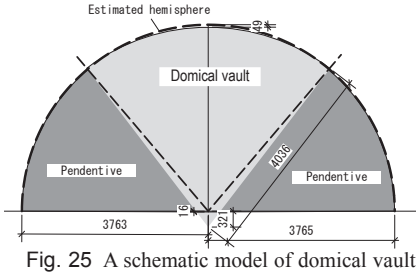

Fig. 25 A schematic model of domical vault of Nuweijis near Amman

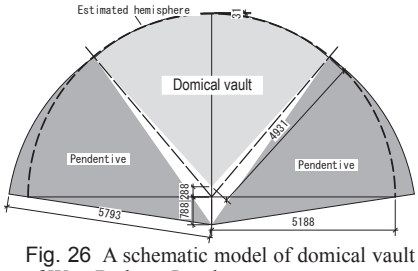

Fig. 26 A schematic model of domical vault of West Baths at Jerash

found. Creswell considered the construction of the West Baths to be not later than the first half of the third century AD judging from the building phases of the city. According to the result of new excavations of 1981-83, the north section of Jerash, including the North Tetrapylon,[41] the North Theater and the North Cardo were not planned in the original layout of the city. Ball says that the North Tetrapylon was built sometime between the middle of the second century AD and about AD 180.[42] This assumption is supported by two pieces of evidence: Firstly, the construction of the North Propylon is not later than the time of the expansion work of the Cardo, which is dated to AD 180, judging from the connection between the streets and the North Tetrapylon.[43] Secondly, the construction of the North Tetrapylon is associated with the construction of the North Theater in AD 165/166, which is supported by the epigraphic evidence of four line inscriptions of the architrave originally located above the central door of the north façade of the scene building, indicating that the building was dedicated, and probably completed at that time.[44] Judging from the excellent character of its structure, it probably belongs to the earlier period of the northern part of the city.

In addition, the Corinthian colonnade surrounding the West Baths has a similar character to the one at the South Cardo. The Corinthian capital from the colonnade of the West Bath has a somewhat small kalathos with two ties of well-developed acanthus leaves (Fig. 21). The inner and outer volutes are raised upward, but they are rather small and simple. The acanthus leaves have small tongue-shaped serrations and there are no holes but only narrow gutters between them. The most characteristic point of the capital from the West Baths is its abacus, which is thin and has no decoration. These characteristics can be seen also on the Corinthian capital from the colonnade of the south Cardo (Fig. 22). In contrast, the Corinthian capital from the North Plaza, which is next to the North Theater, does not look like the one from the West Baths. The capital of the North Plaza has a slender kalathos and is crowning an abacus decorated by tongue leaves (Fig. 23). It is believed that the renovation of the North Decumanus including the North Plaza was later than widening of the South Cardo.[45]

These facts indicate that the construction phase of the West Baths was probably the same as the widening of the south Cardo. It is safe to say, therefore, that the construction of the West Baths belongs to the period when the entire length of the Cardo in the south of the Tetrapylon was widened and its order was changed from Ionic to Corinthian. The rebuilding and widening operation began from the Propylaeum of the Temple of Artemis and continued until soon before the North Tetrapylon (the northern end was never finished). According to the Polish excavations, the date of this project was "not …before the AD 165 and probably not after Marcus Aurelius (AD 161-180)."[46] Therefore, the construction of West Baths was probably during the third quarter of the second century AD.[47]

5. Summary

In the present paper, the author has reported the architectural remains of domical vaults with pendentive remaining in Jordan. In the case of the Baths at Petra, the domical vault is not supported by arches made of voussoir on all four sides but rather by the ashlar walls. In this regard, the case of Petra is missing an element as a domical vault.[48] Nevertheless, the measurements indicate that each of the domical vault and pendentives is created as a hemisphere and their standard deviations are less than a few cm. The gap between the top of the domical vault and of the estimated hemisphere is 4 cm.

Nuweijis near Amman is one of the best preserved examples of domical vault rests on pendentives. The new measurements indicate that the curvatures of the domical vault and of the pendentives are approximately the same. The top of the domical vault is just ca. 5 cm lower than the top of the estimated hemisphere. As Creswell says, it is confirmed that we have 'an exact replica in stone of diagram' (Fig. 1, No. 2).[49] When the frame of the domical vault was removed, the cut stone blocks would have sagged down by their own weight until they were stabilized by friction which it would have probably made the top of the domical vault sink down. It is estimated that the Nuweijis was built in the mid-second century AD.

The Baths at Jerash is also one of the best preserved examples of domical vault rests on pendentives. Both the domical vault and the pendentives are inscribed in hemispheres with high accuracy less than a few centimeters' error. However, the new measurements indicate that the curvatures of the domical vault and of the pendentives are not the same. This possibly means that the domical vault of Jerash was not built all at once, but that each hemisphere was built separately. It is presumed that four aches and pendentives were built at the same time, and then, the upper part was built on the top. It is considered that the domical vault and pendentives of West Baths were built in the third quarter of the second century.

Cut stone voussoir of domical vault has a sphere surface on top and bottom, and other four faces are cut diagonally so as to fit adjoining stones (Fig. 27). To create such a complicated shape was presumably not so difficult for Roman craftsman in this region.[50] The weight of domical vault made of cut stones was considerably too heavy so it would make horizontal thrust, and it was difficult to support without heavy barrel vaults behind the four arches on which the domical vault rests. The curvature of central part rests on pendentive was probably too shallow to build a bigger one. That is why these monuments are relatively small in scale. It is probably impossible to build a domical vault on a square more than 10 m in diameter. In order to solve this problem, we must wait for the next solution of pendentive dome, which was made of brick and mortar. The first appearance of it might be the later dome of Agia Sophia at Constantinople built in AD 573.[51]

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List of the Figures

Fig. 1: Drawings after Jackson 1913, vol. I, p. 39, fig. 10; Fig. 2: Drawing after Rababeh 2005, fig. 6.18; Figs. 3, 7, 9, 14-15, 17 and 20: Photos by the author; Fig. 4: Photo after S. all-Tell 1969, pl. 12; Figs. 5, 10 and 18: Point-clouds images by P. Tokmakidis; Figs. 6, 11 and 19; Drawings by the K. Otsuka; Fig. 8: Drawing by the author; Fig. 12-13, 21-23: Photos by A. Ktistis; Fig. 16: Drawing after Krealing 1938, plan XXVII; Fig. 24: Adam 1994, p. 169, fig. 404.

Abbreviations

Academic Journals

AA	*Archäologischer Anzieger*
ADAJ	*Annual of the Department of Antiquities of Jordan*
JHS	*Journal of Hellenic Studies*

Modern Sources

Adam 1994:	J.-P. Adam, *Roman Building – Material and Techniques*, London, 1994.
Bachmann 1921:	W. Bachmann, C. Waltzinger and T. Wiegand, *Petra, Wissenschaftliche Veröffentlichungen des deutsch-türkischen Denkmalschutz-Kommandos*, Heft 3, Leipzig, 1921.
Browning 1982:	I. Browning, *Jerash and the Decapolis*, London, 1982
Choisy 1899 :	A. Choisy, *Histoire de l'architecture*, Genéve and Paris, 1899 (reprinted in 1982).
Conder 1889:	C. R. Conder, *The Survey of Eastern Palestine*, London, 1889.
Creswell 1979:	K. A. C. Creswell, *Early Muslim Architecture*, 1979.
Hamilton 1939:	R. W. Hamilton, "The Domed Tomb at Sebastya," *The Quarterly of the Department of Antiquity in Palestine Jerusalem*, vol. 8, 1939, pp. 64-74.
Hidaka and Sato 2003:	K. Hidaka and T. Sato (eds.), *Architectural-Structural Survey of Hagia Sophia*, Tokyo, 2003. (in Japanese)
Jackson 1913:	T. G. Jackson, *Byzntine and Romanesque Architecture*, vol. I, Cambridge, 1913.
Kanellopoulos 1994:	C. Kanellopoulos, *The Great Temple of Amman – The Architecture*, Amman, 1994.
Khouri 1986:	E. Khouri, Jerash, *A Frontier City of the Roman East*, London and New York, 1986.
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Mainstone 1988:	R. J. Mainstone, *Hagia Sophia, Architecture, Structure and Liturgy of Justinian's Great Church*, London, 1988.
Mango 1985:	C. Mango, *Byzantine Architecture*, Milano, 1985.
McKenzie 1990:	J. McKenzie, *The Architecture of Petra*, Oxford, 1990.
Rababeh 2005:	S. M. Rababeh, *How Petra was Built: An analysis of the construction techniques of the Nabatean freestanding buildings and rock-cut monuments in Petra, Jordan*, BAR International Series 1460, Oxford, 2005.
Ragette 1980:	F. Ragette, *Baalbek*, New Jersey, 1980.
Sear 1983:	F. Sear, *Roman Architecture*, New York, 1983
Smith 1951:	E. B. Smith, *The Dome*, 1950.
Ward-Perkins 1994:	J. B. Ward-Perkins, *Studies in Roman and Early Christian Architecture*, London, 1994.
White 1984:	K. D. White, *Greek and Roman Technology*, London, 1984
Zayadine 1986:	F. Zayadine (ed.), *Jerash Archaeology Report 1981-83*, Department of Antiquity of Jordan, Amman, 1986.

Notes

1) C. E. Isabelle, *Le Êdifices circulqires et les dôme*, 1855, pp. 70-71; J. R. Rahn, *Über den Ursprung und die Entwicklung des christlichen Central – und Kuppelbaus*, 1866, pp. 69-81; J. Fergusson, *History of Architecture*, II, 1867, pp. 308-310; 3rd ed., I, pp. 433-435; Violle-le-Duc, *Dictionnaire*, IV, pp. 347-367 and VII, pp. 110-114; A. Choisy, *L'Art de bâtir chez les Byzantins*, 1883, pp. 79-80, 88-89, 152, 158-162; Dieulafoy, *L'Art antique de la Perse*, 1885, IV, pp. 72-75; A. Gosset, *Les Coupoles d'Orient*, 1889, pp. 245, 249-252; Lethaby and Swainson, *Sancta Sophia*, 1894, pp. 201-203; Choisy 1899, I, pp. 527-528, and II, pp. 11-13; Millet, *Revue Archéologique*, 4me sér., V, 1905, p. 102; R. Sturgis, *History of Architecture*, I, 1906, pp. 92-3; G. L. Bell, in Ramsay and Bell, *Thousand and One Churches*, 1909, pp. 438-46; A. K. Porter, *Medieval Architecture*, pp. 105-8; G. L. Bell, in *JHS* 30, 1910, pp. 78-9; Diehl, *Manuel d'art byzantine*, pp. 33-7, C. R. de Lasteyrie, *L'Architecture religieuse en France à l'époaue romane*, 1912, pp. 268-70, 272-5; W. R. Lethaby, *Architecture*, 1912, pp. 57-8, 112-13; J. Rosintal, *Pendentifs, Trompen und Stalaktiten*, 1912, pp. 8-18, T. G. Jackson, *Byzntine and Romanesque Architecture*, vol. I, 1913, pp. 39-40; J. Strzygowski, *Die Baukunst der Armenier*, 1918, pp. 359-361, 484-485; J. Strzygowski, "Die Entstehung der Kreuzkuppelkirche," *Zeitschrift für Geschichte der Architektur*, 1919, VII, pp. 51-77; J. Strzygowski, *Ursprung der christlichen Kirchenkunst*, 1920, p. 52; G. T. Rivoira, *Architettura romana*, 1921, pp. 135-7, 192-8, 210, 213-16, 319, 328-31; English trans., pp. 108, 152-9, 171, 172-4, 263-4, 273-5; O. M. Dalton, *East Christian Art*, 1920, pp. 84-5; W. J. Anderson and R. B. Spiers, *Architecture of Ancient Rome*, Ashby (ed.), 1927, pp. 82, 138; J. Pijoan, *History of Art*, II, 1927, pp. 56-7; J. A. Hamilton, *Byzantine Architecture*, 1933, pp. 14-20; J. Ebersolt, *Monuments de l'Architecture byzantine*, 1934, p. 31, n. 1; R. Zaloziecky, *Die Sophienkirche in Konsantinopel*,1936, pp. 218-30, E. H. Swift, *Hagia Sophia*, 1940, p. 163; E. B. Smith, *The Dome*, 1950, Chap. III; E. H. Swift, *Roman Sources of Christian Art*, 1951, pp. 111-25, Figs. 60-63 and pls. XX-XXIII; Creswell 1979, Vol. 1, Part 2, pp. 450-471; Sear 1983, pp. 78-79, Fig. 41; Mango 1985, pp. 11-14, Figs. 6-11.
2) Choisy 1899, vol. I, pp. 518-519.
3) Hamilton 1939, pp. 64-74. The Pagan Tomb at Samaria has square walls ca. 3 x 3 m supporting an intact dome of stone blocks. (Hamilton 1939, fig. 3) There are four arches on each side of the massive walls ca. 90 cm thick. The structure is quite similar to those at Nuweijis and Jerash. The Tomb at Sebastya is dated in or soon after the reign of Septimius Severus, AD 193-211, from the character of the sarcophagi discovered from its inside. (Hamilton 1939, p. 66)
4) Creswell 1979, pp. 450-470.
5) Rababeh 2005, pp. 166-174.
6) R. Nakashima *et. al*., "Studies of Ancient Mediterranean Cities (132) : A Study of the dome in the ancient architecture of Mediterranean and west Asia," *Architectural Institute of Japan, Kyushu-Branch*, 2001, pp. 633-63 (in Japanese); Y. Okada, "Vaulting Masonry in Late Antiquity West Asia," *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*, F-2, History and theory of architecture 2007, pp. 125-126 (in Japanese); Y. Okada, "A follow-up study on the domical vault at Gadara, Jordan," *The 13th Annual Meeting of Japan Society for Hellenistic-Islam Archaeological Studies*, Kanazawa, 21-22 October 2006, pp. 99-102 (in Japanese); Y. Okada, "A domical vault at Gadara, Jordan," *The 12th Annual Meeting of Japan Society for Hellenistic-Islam Archaeological Studies*, Kanazawa, 8-9 October 2005, pp. 60-61 (in Japanese).
7) White 1984; Adam 1994.
8) I would like to thank Prof. Dr. Okada of Kokushikan University, the leader of the architectural mission, and Prof. Dr. K. Onuma, the general director of the research group. The research was supported by JSPS KAKENHI, Grant-in-Aid for Scientific Research on Priority Area (2005-2009), "Formation of Tribal Communities in the Bishri Mountains, Middle Euphrates." The result of the five-year project was published in a symposium proceeding. K. Onuma (ed.), *Supervising Team of the Research Project Formation of Tribal Communities in the Bishri Mountains, Middle Euphrates*, "Integrated Research in the Middle Euphrates, Syria," special issue of *AL-RĀFIDĀN: Journal of Western Asiatic Studies*, Kokushikan University, Tokyo, 2010. The present research is developed from the basic study of the architectural group.
9) The author would like to express my sincerest thanks to Dr. Ziad al Saad, the general director of department of antiquities in Jordan, who kindly helped me to realize this project. The author would also like to express his deep gratitude to Dr. Kalil Hamadan, and to Mr. Fusein Dahbour, department of antiquities, who helped me conduct the actual proceeding. This project could not have begun without their understanding and interest in this research. In addition, the author would like to show his gratitude to two academic referees: Prof. Ken Matsumoto, Director of the Kokushikan University Expedition to Umm Quais, and Prof. Isamu Taniguchi, President of Kumamoto University. They kindly recommended my research and helped me realize the first season. Mr. Ehab Jariri, surveyor of the department of antiquity in Amman, kindly helped me to access the monuments in the archaeological sites. I would like to thank Dr. Ahmad Alshami, director of the department of antiquity in Jerash and Dr. Tahani Mohammed Al-Salhi, director of cultural resources management in Petra; they kindly helped me to access the subject on which I have worked. The author also would like to thank Prof. Konstantinos Tokmakidis, professor of the school of topography and survey engineering, Aristotle University of Thessaloniki and his son Panagiotis Tokmakidis, surveyor in Thessarlniki. Moreover, photographer Anastasios Ktistis of Thessaroniki kindly helped my fieldwork in Nuweijis and took architectural photos. Finally, the author would like to show his gratitude to Mr. Akira Mitsuyama and Mr. Sotaro Yamasaki, postgraduate students of Kumamoto University in 2011 and to Mr. Kazuki Otsuka, postgraduate student in 2013.

   In the first season, the Nuweijis at Amman was surveyed between the 4th and 13th of January, 2011, and a non-reflective total station (Leica Flexline TS06, angle accuracy 3", range flexpoint 30m) was used. As a result, about 2,500 points were measured at this site, and architectural drawings were developed using AutoCAD 2008. In the second season, the Nuweijis at Amman, the West Bath at Jerash and the Roman Bath at Petra were surveyed between the 4th and 11th of September 2011, and a 3D laser-scanner Faro (FARO FOCUS 3D) was used for the mission. The third season, the Nuweijis and other Roman buildings were surveyed from a chronological point of view, with special focus on the architectural ornamentations of the entablature, between the 1st and 9th of September, 2012.
10) FARO Focus 3D.
11) "A Djerach, le raccord entre le plan carré et la calotte sphérique est obtenu par des pendentifs dont la forme est en triangle sphérique..." Choisy 1899, vol. I, p. 519.
12) The drawing of Choisy is probably not West Baths but North Tetrapylon, because of the podium. As far as the author knows, North Tetrapylon at Jerash was already corrupted at least until 1971, and was restored in 1981.
13) Jackson 1913, pp. 39-40.
14) *Ibid*, p. 40.
15) Underlined by the author. Creswell 1979, vol. I, part 2, p. 460.
16) Creswell 1979, pp. 470ff; Mango 1985, p. 11, note 5.
17) Mango 1985, p. 11.
18) Sear 1983, p. 79, Fig. 41d.
19) Jackson 1913, p. 39.
20) R. E. Brünnow and A. von Domaszewkis, *Die Provincia Arabica*, vol. 1, Straßbrug 1904, pp. 179, 316; Bachmann 1921, pp. 45-48 figs. 39-42; K. Ronczewski, "Kapitelle des El Hasne in Petra," *AA*, 1932, p. 90; P. J. Parr, "Recent discoveries in the Sanctuary of the Qasr Bint Far'un at Petra: Account of the recent excavations," *ADAJ* 12-13, 1967-8, 12-13, pp. 7-9; S. all-Tell, "The New Archaeological Studies in Jordan," *ADAJ* 14, 1969, p. 29 (in Arabic); F. Zayadine, "Fouilles classiques récentes en Jordanie," *Annales archéologiques arabes syriennes* 21, p. 154; F. Zayadine, "Tempel, Gräber, Töpferöfen," in M. Lindner (ed.), *Petra. Neue Ausgrauben und Entdeckungen*, München, 1986, p. 217; F. Zayadine, "Decorative Stucco at Petra and other Hellenistic Sites," *Studies in the History and Archaeology of Jordan* 3, pp. 137-139; I. Browning, *Petra*, 1st ed., London, 1973, pp. 41, 147-150; A. Negev, "Die Nabatäer," *Antike Welt* Suppl. 7, pp. 26, 29; Z. Ismail, "Les Chapiteaux de Pétra," *Le Monde de la Bible* 14, p. 28; M. M. Khadija, "16 Jahre Feldarchäologie in Petra," in M. Lindner (ed.), Petra und das Königreich der Nabatäer 3, Munich, 1980, pp. 208-209; M. Lindner, "Archäologische Erkundungen des Der-Plateaus oberhalb von Petra (Jordanien) 1982 und 1983," *AA* 1984, p. 610; M. Lindner *et al*., "New Explorations of the Deir-Plateau (Petra) 1982/83," *ADAJ* 28, p. 166; R. Wennig, *Die Nabatäer-Denkmäler und Geschichte*, Göttingen, 1987, pp. 226-7, 235, 303; Rababeh 2005, pp. 166-174.
21) S. all-Tell, "The New Archaeological Studies in Jordan," *ADAJ* 14, 1969, pl. 12 a; McKenzie 1990, pl. 76-a.

22) McKenzie 1990, p. 138.
23) Bachmann 1921, p. 47.
24) Bachmann 1921, pl. 14; S. all-Tell, "The New Archaeological Studies in Jordan," *ADAJ* 14, 1969, pl. 12 a; McKenzie 1990, pl. 76b; Rababeh 2005, p. 167, fig. 6.18.
25) Rababeh 2005, pp. 166-174.
26) S. all-Tell, "The New Archaeological Studies in Jordan," *ADAJ* 14, 1969, pl. 12-b.
27) McKenzie 1990, p. 51.
28) Conder 1889, p. 172.
29) Conder 1889, pp. 172-174.
30) Creswell 1979, vol. 1, part 2, pp. 460-461.
31) Conder 1889, p. 174.
32) Rivoira, *Roman Architecture*, p. 173.
33) Creswell 1979, vol. I, part 2, p. 461. As for the date of the Temple of Bacchus, Creswell agreed with Krencker's opinion that the style of the Temple of Bacchus is not the same as that of the Great Temple, but it corresponds perfectly with the architecture of the great court, which is dated to Antonius Pius (AD 138-161). (Krencker 1921, p. 86) Fischer agreed with Krencker's opinion. (C. S. Fisher, "The 'Forum," in: Krealing1938, pp. 155-157)
34) Ragette 1980, p. 104.
35) C. B. Welles, "The Inscription," in: Kraelling 1938, pp. 402-403, pl. CIX-b; Browning 1982, figs. 88-89 (see the left side of the inner façade of the Propylaeum of the Temple of Artemis).
36) Kanellopoulos 1994, p. 61, fig. 111. Two other Roman tombs are known in Amman. The West Tomb in the downtown area was reported by Conder in the end of 19th century AD, but it no longer remains. (Conder 1889, pp. 43-45) The West Tomb was located on the way to the downtown area, near the Nymphaeum. It is a square structure of masonry stone, and was once roofed with a dome, probably like a dome from the Mausoleum of Bizzos. (Creswell 1979, vol. I, part 2, Fig. 504) When Conder visited this tomb, about three-quarters of the circle remained. Its arrangement does not look like a pendentive dome. Large voussoirs on the four corners are projecting inwards and their faces being cut to the arc. (Conder 1889, p.44; Creswell 1979, vol. I, part 2, Fig. 498) There is also another Roman tomb, which is located in the east outskirts of Amman. It is a massive square structure of masonry stone. The upper tunnel volute supports the roof. Five sarcophagi remain inside.
37) Kanellopoulos 1994, pp. 52-53, figs. 92-94, 97-98.
38) Concerning the architectural ornamentation, the other Roman buildings, including the South Propylon, the Southeast Temenos Gate, and the Temenos, were probably built in this period. (Kanellopoulos 1994)
39) Browning 1982, p. 83, map 3; the West Baths, pp. 176-168, fig. 99.
40) Kraeling 1938, p. 23, pl. VI-b.
41) The North Tetrapylon at Jerash was fully reconstructed by the Department of Antiquity of Jordan during a research project between 1981 and 1983. The reconstructed North Tetrapylon is crowned with a domical vault supported by pendentives, but no original fragments were reported. (W. Ball *et al*., "The North Decumanus and North Tetrapylon at Jerash: An Archaeological and Architectural Report," in Zayadine 1986, pp. 385-386.)
42) Ball *op. cit*., p. 389.
43) Ball *op. cit*., p. 386.
44) J. D. Stewart, "The Architecture of the Roman Theater," in Zayadine 1986, p. 229; Ball *op. cit*., p. 389, fn. 72.
45) Ball *op. cit*., p. 393. (phase 5)
46) Ball *op. cit*., p. 386, fn. 48. Oral information.
47) Recently, Khouri said "inscriptions found here confirm that this was a public baths complex from the Byzantine period, built by Bishop Placcus in 454-5 and restored in 584." Khouri considered that the West Baths was reconstructed in the Byzantine period on the earlier Roman baths, because it has standard layout of Roman baths. Khouri's estimation is probably correct, but it does not say anything whether the domical vault and its pendentives are from Roman or Byzantine period. The North Tetrapylon, located 50 m north from the West Baths, which had domical vault with pendentives as well, and is dated to the same period to the West Baths. According to these circumstances, it can be hardly believed that the domical vault of West Baths is reconstructed in Byzantine period. Khouri 1986, pp. 116-117.
48) McKenzie 1990, p. 51. There are no practical arches mentioned by Rababeh. (Rababeh 2005, p. 166)
49) Creswell 1979, p. 460.
50) Barrel vault and cross vault made of cut stone can be seen elsewhere from south Turkey to Levant; foundation of North Stoa of Agora at Izmir (with stone rib!), vomitoria under the auditorium of Theatre at Miletus, vomitoria under the auditorium of Theatre at Side, cross-section of two corridors of Theater of Philippopolis in Syria, corridor under the colonnaded street at Bostra, vomitoria under the auditorium of Theatre at Bostra, corridor under the Temple of Jupiter at Baalbek, vomitoria under the auditorium of North and West Theatres at Gadara, and so on.
51) The initial dome of Agia Sophia considerably belongs to the first type of dome, or domical vault. Since the eastern part of the main dome and the eastern semidome fell down due to the earthquake in 557, some parts of the present pendentive dome is of the reconstruction in later period. Mainstone 1988, pp. 89ff, 209ff, figs. 106, 237. Hidaka and Sato 2003, pp. 33-34.

和文要約

正方形平面のモニュメントに外接半球をのせ四辺を切り取る方法がローマ時代のレバントに見られることは、すでに 19 世紀末から知られていた。その後ハミルトンやクレスウェルらの成果によって、この地域に多くの実例があることが報告されている。こうした過去の研究から、当時の建設技術者たちが、正方形平面の上に半球を載せ、四辺をアーチで支え、四隅を球面三角形で納める方法を熟知していたことが伺える。もし球面三角形と上の半球が同じ半径の球面に沿って作られたのであれば、互いの曲率は同じはずであるが、その詳しい形状は、既存実測図だけでは確かめることができない。そこで、事前の踏査に基づいて候補をリストアップし、これらの中でも最も古くかつ残りが良いと思われるヨルダンに残る 3 つの実例（ペトラの浴場、アンマンのヌウェイジズ、ジェラシュの西浴場）についてレーザー測量技術を用いて実測調査を行った。本稿ではその調査結果を報告すると共に、最新の考古学的成果から建設年代を新たに推定し、発展史上の位置づけを考察する。

本稿で取り扱う、背の低い半球が四辺のアーチと四隅の球面三角形とで支持される方法（Fig. 1, No. 2）は、通常のペンデンティブ・ドームとは異なる。一般にペンデンティブ・ドームと呼ばれる手法は、四辺のアーチの頂部を切り取り、四隅の球面三角形のペンデンティブの上に、さらに正方形に内接する半径の小さな半球をのせたものである（Fig. 1, No. 4）。そのため、前者では球面三角形とその上にのる曲面は連続した曲面になるが、後者では球面三角形の曲率は中央ドームの曲率よりも大きくなる。またクレスウェルが詳細に明らかにしマンゴーが支持したように、前者と後者の球面三角形＝ペンデンティブの形状は、本質的に同じである。しかし、双方をペンデンティブ・ドームと呼ぶのは不都合である。マンゴーは、前者がペンデンティブから連続的に切石や煉瓦が積まれて上部を形成することに注目して、ドーム状ヴォールトと呼んだ。ドームがヴォールトの一種であるとの理解はシアーも受け継いでる。そこで本稿ではマンゴーの定義に従い、前者を「ドーム状ヴォールト（Fig. 1, No. 2）」、後者を「ペンデンティブ・ドーム（Fig. 1, No. 4）」と区別し、四隅の球面三角形をペンデンティブと呼ぶ。

ペトラの地下浴場のドームは、朱色の砂岩の切石で作られており、3 つの部屋の一つは、正方形の部屋の上に球形の屋根を載せている。しかし、中央の背の低い半球を支える四辺は、半円形の壁で支えられているものの、迫り石で作られたアーチが存在しない。Rababeh の断面図にあるように、これまで迫り石のアーチの上に半球が載ると理解されてきたが、実際にはそのような構造は存在しなかった。また、ペトラの地下浴場が発掘された際には、この東壁は完全に崩れていて、修復されていたことも文献によって確認された。またこの発掘時の写真から、ペンデンティブの石積みが、持ち送りではなく迫り石であることも確かめられた。レーザー測量による計測の結果、ペンデンティブを含めたドーム状ヴォールト全体に最も近い半球は、3.55 m（標準偏差 0.037 m）であった。遺構の残りが悪いわりに、比較的半球に近い形状をしている。地下浴場の建設年代は、建築装飾の様式と考古学的資料から、紀元 1 世紀と推定される。

アンマン近郊のヌウェイジズは、2 つのトンネル・ヴォールトの交差部にドーム状ヴォールトが載っており、四辺のアーチとそれらに挟まれた球面三角形ペンデンティブが支えている。ドーム状ヴォールトは迫り石を放射状に並べて作られており、頂部には花模様のあるキーストーンがある。レーザー測量による計測の結果、ペンデンティブを含めたドーム状ヴォールト全体に最も近い半球は、3.77 m（標準偏差 0.047 m）であった。ペンデンティブの曲率は半球の曲率にかなり近いが、ドーム状ヴォールトの曲率は半球の曲率よりもやや小さい。そのためドーム状ヴォールトの中心は、半球の中心よりも 32 cm 低い位置にある。またドーム状ヴォールトの頂部は、想定される半球の頂部よりも僅か 5 cm ほど低くなっている。ヌウェイジズは考古学的資料に乏しく、建築装飾の様式分析によって、アンマンのローマ神殿（後 166 年、碑文）、ジェラシュのアルテミス神域の西プロピロン（後 150 年、碑文）、バールベックのバッカス神殿（後 2 世紀後半、建築装飾）に類似することから、後 2 世紀半ばと推定される。

ジェラシュの西浴場は、この地域に残るドーム状ヴォールトの中で最も大きい。ペンデンティブとアーチで支えられたドーム状ヴォールトは迫石を放射状に並べて作られており、頂部には一つの石材で出来た天窓がある。レーザー測量による計測の結果、ペンデンティブを含めたドーム状ヴォールト全体に最も近い半球は、5.19 m（標準偏差 0.040 m）であった。ドーム状ヴォールトの曲率は半球の曲率よりも小さく、ペンデンティブの曲率は半球の曲率よりも大きい。そのためドーム状ヴォールトの中心は、半球の中心よりも 29 cm 高い位置にあり、逆にペンデンティブの中心は半球の中心よりも約 79 cm 低い位置にある。またドーム状ヴォールトの頂部は仮想半球よりも 3 センチ低くなっている。西浴場は、北テトラピロンから南側のカルドの道幅が拡張され、イオニア式オーダーからコリント式オーダーに建て替えられた直後（後 2 世紀半ば）の、後 2 世紀第 3 四半期と推定される。

今回の調査によって、以下のことが確かめられた。これまで最初期の実例とされていたペトラの浴場（後 1 世紀）は、四辺のアーチの一部が存在しないが、形状は極めて半球に近い。アンマン近郊のヌウェイジズ（後 2 世紀半ば）とジェラシュの西浴場（後 2 世紀第 3 四半期）は、切石の迫り石で作られており、ドーム状ヴォールトとペンデンティブはかなり正確な球面として作られている。このように切石によるドーム状ヴォールトは、レバントでは 2 世紀中ごろから始まる事が確かめられた。同様の手法は 6 世紀ごろまであることが報告されている。

切石によるドーム状ヴォールトは、ヘレニズムにまで遡るこの地域の石工技術の伝統によって支えられていた。ドーム状ヴォールトの迫石は、底面と上面が球面で、残る四面は隣り合う石材に併せて斜めに切る必要があるため、複雑な形状をしている。このような迫石の加工は、熟練した当時の石工にとってはそれほど難しくなかったようである。切石のドーム状ヴォールトは重く、強い水平応力として四辺のアーチに伝わったため、アーチの背後に重たいトンネル・ヴォールトの支えがなければ不安定であったに違いない。また背の低いドーム状ヴォールトは、曲率が大きいため、大スパンのドームには適していなかった。本稿で取り上げた実例の直径がいずれも 10 m 以下であるのはそのためであろう。この問題を解決には、アーチの上に正方形に内接する球を載せた、いわゆるペンデンティブ・ドームの発明（6 世紀後半）を待たねばならなかった。

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