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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吉 隆一

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 vousoir 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

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 pendentifs) and about its general development.8 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.9 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.9 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 Jerusalem (Table 1).4 Recently, the Baths at Petra is nominated as one of the earliest candidates of this kind of dome.9 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.4 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.9 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.9 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).”10 Judging from his axonometric drawing, the monument of Jerash is supposed to be North Tetraklyon, 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 FGHJ 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).”10 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

<table>
<thead>
<tr>
<th>Monument</th>
<th>Element</th>
<th>Material</th>
<th>Construction date</th>
<th>Restoration</th>
<th>County</th>
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</thead>
<tbody>
<tr>
<td>Baths at Petra</td>
<td>pendentive, domical vault</td>
<td>cut stone</td>
<td>second half of the 1st century (pottery and ornamentation)</td>
<td>partly repaired (1968-69)</td>
<td>Jordan</td>
</tr>
<tr>
<td>Niwajis near Amman</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>middle of the 2nd century (architectural ornamentation)</td>
<td>partly repaired (?)</td>
<td>Jordan</td>
</tr>
<tr>
<td>West Baths at Jerash</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>second half of the 2nd century (architectural ornamentation)</td>
<td>original</td>
<td>Jordan</td>
</tr>
<tr>
<td>North Tetrapotamon at Jerash</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>second half of the 2nd century</td>
<td>reconstructed (1981-83)</td>
<td>Jordan</td>
</tr>
<tr>
<td>Pagan Tomb at Samaria</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>beginning of the 3rd century</td>
<td>original (?)</td>
<td>Israel</td>
</tr>
<tr>
<td>Underground Tomb at Gadara</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>beginning of the 3rd century</td>
<td>original (?)</td>
<td>Israel</td>
</tr>
<tr>
<td>Ibrad</td>
<td>pendentive, domical vault</td>
<td>cut stone</td>
<td>later than 4th century (architectural style?)</td>
<td>original (?)</td>
<td>Jordan</td>
</tr>
<tr>
<td>Golden Gate of Jerusalem</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>between 616 and 629/7 (historical context)</td>
<td>original</td>
<td>Syria</td>
</tr>
<tr>
<td>Double Gate of Jerusalem</td>
<td>arch, pendentive, domical vault</td>
<td>cut stone</td>
<td>same to Golden Gate (?)</td>
<td>original</td>
<td>Israel</td>
</tr>
</tbody>
</table>

### 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…”

Cresswell reported many examples of the first type of dome (shallow dome on pendentives) of Levant. Cresswell 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).” Cresswell 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. 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.”

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 Gallia Placidia at Ravenna and many parts of Agia Sophia at Constantinople. The second type of dome is pendentive dome, which appeared in Byzantine architecture.

### 2. Baths at Petra

#### 2-1. Architectural remains

Baths at Petra 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 stucco 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. 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. Every two bays have a semicircular niche, at the tops of which were traces of a conch. 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). There are four spherical-triangles with five courses on the corners. 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). 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 walls 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. 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. Quasayr an-Nuweijis means "palace of the princes." 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. Creswell reports with good photographs and discusses the spherical-triangle pendentive; however, no architectural report has appeared yet.

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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

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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...
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 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 upper 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. Rivoira accepted this estimate of the second century AD., but he probably did not know the interior of the Nuweijis at that time. 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. Indeed, the frieze ornamentation of palm motif and the combination of decorations at the geison is almost the same as at Nuweijis. 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).

The combination of the architectural ornamentation of the entablature, including the vegetable and figural motif of the frieze, also confirm the construction date. The entablature from the Roman Temple at Amman has a similar ornamental motif to that of Nuweijis (Figs. 14, 15). It must be noted that the palm motif of under part of the sina and the vegetable motif of the frieze from the Roman Temple are the same as the ornamentation of Nuweijis. The Roman Temple at Amman is securely dated to the time when Geminianus Marciannos was the governor of Provincia Arabia (AD 161 - 166). 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. 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. 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
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, 43) 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. 44) 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. 45) 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. 46) 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 tiers 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. 47)

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).” 48) Therefore, the construction of West Baths was probably during the third quarter of the second century AD. 49)

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. 50) 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.

Table 2 Measurements of three monuments in Jordan

<table>
<thead>
<tr>
<th></th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
<th>Radius (m)</th>
<th>N. of Points</th>
<th>StdDev (m)</th>
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<td>Domical vault</td>
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<tr>
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<td>11.955</td>
<td>2.095</td>
<td>3.765</td>
<td>232,778</td>
<td>0.047</td>
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<td>Jerash</td>
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<tr>
<td>Domical vault</td>
<td>700.849</td>
<td>-755.595</td>
<td>1.198</td>
<td>4.931</td>
<td>248,738</td>
<td>0.027</td>
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<tr>
<td>Pendentives</td>
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<td>0.122</td>
<td>5.793</td>
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<td>Domical vault and pendentives</td>
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<td>5.188</td>
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<td>0.040</td>
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Original point is following in the local topographical point of each site.

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
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).16 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 vousoir 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.60 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 573.61

Acknowledgments

This study was supported by JSPS KAKENHI, Grant-in-Aid for Young Scientists (B), Grant Number 22760490, "A study of the ancient domical architecture in Near Middle East by use of the 3D digital measuring techniques."

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. Kniss; Fig. 16: Drawing after Kraeling 1938, plan XXVII; Fig. 24: Adam 1994, p. 169, fig. 404.

Abbreviations

Academic Journals

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<th>AA</th>
<th>Archäologischer Anzeiger</th>
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<td>Annual of the Department of Antiquities of Jordan</td>
</tr>
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<td>JHS</td>
<td>Journal of Hellenic Studies</td>
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Modern Sources

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 inscribed in hemispheres with high accuracy less than a few centimeters’ error. However, the new measurements indicate that the curvatures of the domical...
23) Bachmann 1921, p. 47.
33) Creswell 1979, vol. 1, 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 agrees with Krencker’s opinion. (C. S. Fisher, “The Forum,” in: Kraeling 1938, pp. 155-157)
35) C. B. Welles, “The Inscription,” in: Kraeling 1938, pp. 402-403, pl. CIX-b; Browning 1982, figs. 88-89 (see the left side of the inner façade of the Propyleum 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. 1, 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. 1, 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.
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.
45) Ball op. cit., p. 393. (phase 5)
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 Rabahbeh. (Rabahbeh 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ンバントに見られるのは、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ベリーの成果によって、この地域に多くの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、当時の建築技術者たちが、正方形平面の上に半球を載せ、西辺をアーチで交え、西辺を球面三角形で納める方法を経営していたことが示唆される。もし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、互いの曲率は同じであるが、それと異なる形状は、既存実例だけでは確かなことではない。そこで、事前の踏査に基づいて侯補リストアップし、これらのの中でも最も古くかつ残りが良いと思われる6つの例（ペトラの浴場、アンマンのヌェィジー、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、現存の考古学的成果から建築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で与えられる方策は、正方形のアーチの頂部を切り取る、四隅の球面三角形ベンチネッジが元になる、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）。そのために、前者では球面三角形とその上のある面を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。そこでケルク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＝ベンチネッジの形状は、本質上同じである。しかし、都合をベンチネッジ・ドームと呼ぶのは都合が悪い。マンゴー、前者がベンチネッジから統計的に切り取って煉瓦が積み上げて上部を形成することに注目して、ドーム状ヴォルトと呼んだ。ドームがヴォルトの一種であるとの理解はもうと受け難いので、そこで本稿ではマンゴーの定義に従い、前者を「ドーム状ヴォルト」（Fig. 1 No. 2）、後者を「ベンチネッジ・ドーム（Fig. 1 No. 4）」と区別し、四隅の球面三角形をベンチネッジと呼ぶ。

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つの歯の一部は、正方形の頂部の球面に煉瓦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、追加で作られたアーチは存在しない。Rababehの断面図にあるように、これまで追加のアーチのように半球が載ることが理解されてきたが、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、東側の壁は完全に崩れていて、復旧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、ベンチネッジの石積みが、持ち送りではなく追加で作られるものであることを確認した。レーザー測量による計測の結果、ベンチネッジを含めたドーム状ヴォ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。遺構の残りは、いわゆるノースウェイジ・ペトラの交差部にドーム状ヴォルトが載っており、四辺のアーチとそれらに挟まれた球面三角形ベンチネッジが支えている。ドーム状ヴォルトは石造りの放射状に並べて作られており、頂部には花模様のあるキリスト体がある。レーザー測量による計測の結果、ベンチネッジを含めたドーム状ヴォ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。ベンチネッジの曲率は半球の曲率にかなり近いが、ドーム状ヴォ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ルトの中は、半球の中心よりも32 cm低い位置にある。またドーム状ヴォルトの頂部は、虚線で示される半球の頂部よりも僅か5 cmほど低くなっている。ベンチネッジは考古学的な資料にとらえ、建築様式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殿の西プロピオン（後150年、碑文）、ハルベックのパシカ神殿（後2世紀半、建築装飾）に類似することから、後2世紀半と推定される。

ジェラシュの西部は、この地域に残るドーム状ヴォルトの中でも最大である。ベンチネッジとアーチで支えられたドーム状ヴォルトは追加で放射状に並べて作られおり、頂部には一つの石材で出来た天蓋がある。レーザー測量による計測の結果、ベンチネッジを含めたドーム状ヴォ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。ドーム状ヴォルトの曲率は半球の曲率より少し小さく、ベンチネッジ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ルトの中心は、半球の中心より29 cm高い位置に、逆にベンチネッジの中心は半球の中心よりも約79 cm低い位置にある。またドーム状ヴォルトの頂部は仮想半球よりも3センチメートルほど低くなっている。西部は、北テトリノから南側のカルドの道路が拡張され、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3四半期に推定される。

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は存在しないが、形状は極めて半球に近い。アンマン近郊のヌェィジー（後2世紀半ば）とジェラシュの西部（後2世紀第3四半期）は、切石の追加で作られており、ドーム状ヴォルトとベンチネッジはかなり正確な面積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ルトは、レバントでは2世紀半ばから始まる事実が確認された。同様の手法は6世紀ごろまであることと報告されている。

切石によるドーム状ヴォルトは、ヘレンズムにまで達するこの地域での石工技術の伝統によって支えられている。ドーム状ヴォルトの追加は、底面と上端が球面で、残る四隅は隣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。このような追加の加工は、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ルトは重く、強い鉄力効応としない四辺のアーチに伝わったため、アーチの背に重いトモス・ヴォルトの支えになされず不安定であったに違いない。また背の低いドーム状ヴォルトは、曲率が大きく、大スパンのドームには適していない。本稿で取り上げた実例の直径がいずれも10 m以下であるのをそのためであろう。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、いわゆるベンチネッジ・ドームの発明（6世紀後半）を持たねばならなかった。

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