

Materials and Construction of the Pantheon in Relation to the Developments in Vaulting in Antiquity

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In this paper I discuss the Pantheon in relation to earlier development in vaulted structures in Imperial Rome. I focus on those constructional elements that have traditionally been considered most critical in the success of the monument: the relieving arches, the light-weight caementa, and the step-rings.

I begin at the Theater of Marcellus (17 BC), where there occurs one of the earliest examples of the combination of relieving arches and concrete vaults into a coherent structural system. The design of the theater required that the seating of the *cavea* be elevated on vaults while also providing a corridor to access the lower rows of seating, where the most prestigious spectators were seated. This configuration resulted in floors at different levels in which the walls did not always align. The builders' solution was to insert relieving arches into the curving wall of the *Passaggio dei Cavalieri* in places where there was no support directly underneath it (fig. 1). These arches protected the vaults that run below by directing the load of the wall to the underlying radial walls.

By the time the Colosseum was dedicated in AD 80, theaters and amphitheaters were becoming evermore complex, and the builders were adding to their repertoire of structural elements. At the Colosseum they employed the same type of brick relieving arch as the ones at the Theater of Marcellus, but in this case the ends of the arches were positioned above travertine vaulting ribs built into the underlying vaults

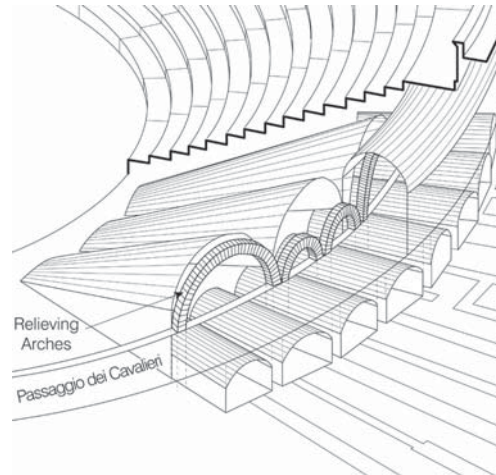


Fig. 1: Theater of Marcellus. Detail of relieving arches in wall spanning underlying substructure vaults.

(fig. 2). These sections of the vaults supported significantly increased loads, so the builders reverted to the use of the travertine voussoir arch as reinforcement. Conceptually, they intended to divert loads away from vaults and also to reinforce the vault to compensate for the added loads. The combination of relieving arches and vaulting ribs worked together to create a three-dimensional system for controlling the forces within the structure in a more complex manner than had hitherto occurred.

In the following decade in the Domitianic Vestibule (AD 81–92) at the base of the Palatine, the builders created a whole series of relieving arches within the walls (fig. 3). Here double relieving arches (semicircular over flat) occur

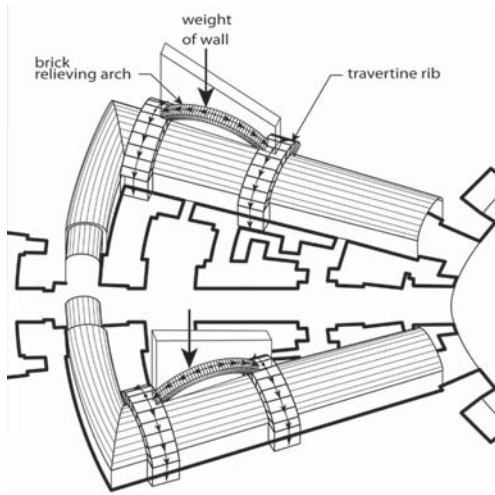


Fig. 2: Colosseum. Detail of relationship between relieving arches in ground level walls and vaulting ribs in hypogea vaults.

in three tiers in all three of the standing walls of the largest hall. They are aligned one above the other and correspond to niches at ground level in each wall, so in effect each niche has three vertical tiers of double relieving arches above it. However, the arches are not always aligned horizontally from one wall to the next. The fact that the putlog holes for the scaffolding often align with the bottom or top of the arches suggests that the arches were strictly integrated into the construction process. The purpose of the arches here is less obvious than at the Colosseum, but they were probably used in this very tall (c. 28 m) and thick (2.4–2.9 m) wall as means of consolidating the fabric of the wall and controlling settlement as the mortar cured so that the construction could proceed upward quickly without a great lag time between layers of walling. Since both ancient and modern concrete gain strength slowly over a period of time, each demonstrates the phenomenon known as «creep», which is the slow deformation of the material over time. It is most pronounced in the first six months as the mortar gains its strength.¹ The relieving arches, therefore, would provide a structural compo-

1 Darwin/Nilson 1997, 33–52.



Fig. 3: Domitianic Vestibule, Palatine. Series of relieving arches in walls.

nent to the wall to help prevent excessive creep or settlement in any one place within the wall and to direct the loads to the thicker parts of the wall between the niches.

One piece of evidence in favor of this proposal is the relieving arch found in the cryptoporticus under the Baths of Trajan, which has painted inscriptions on it. Rita Volpe² has shown that the inscriptions refer to dates that appear to mark the completion of various phases of construction (fig. 4). These dates are interesting because they show us that the arch was built in stages along with the infill underneath the intrados. As there is only one day between the top of the infill (April 16) and the walling at the extrados (April 17), the crown of the arch must have been completed between April 12 and April 16, when the infill under the crown of the arch was added. This sequence would allow the crown of the arch time to settle into place and the mortar to gain its strength so that the arch would be more effective in transferring the load. Janet DeLaine has argued for a similar process based on constructional evidence in a relieving arch at the Baths of Caracalla.³

2 Volpe 2002, 384–390.

3 DeLaine 1997, 152.

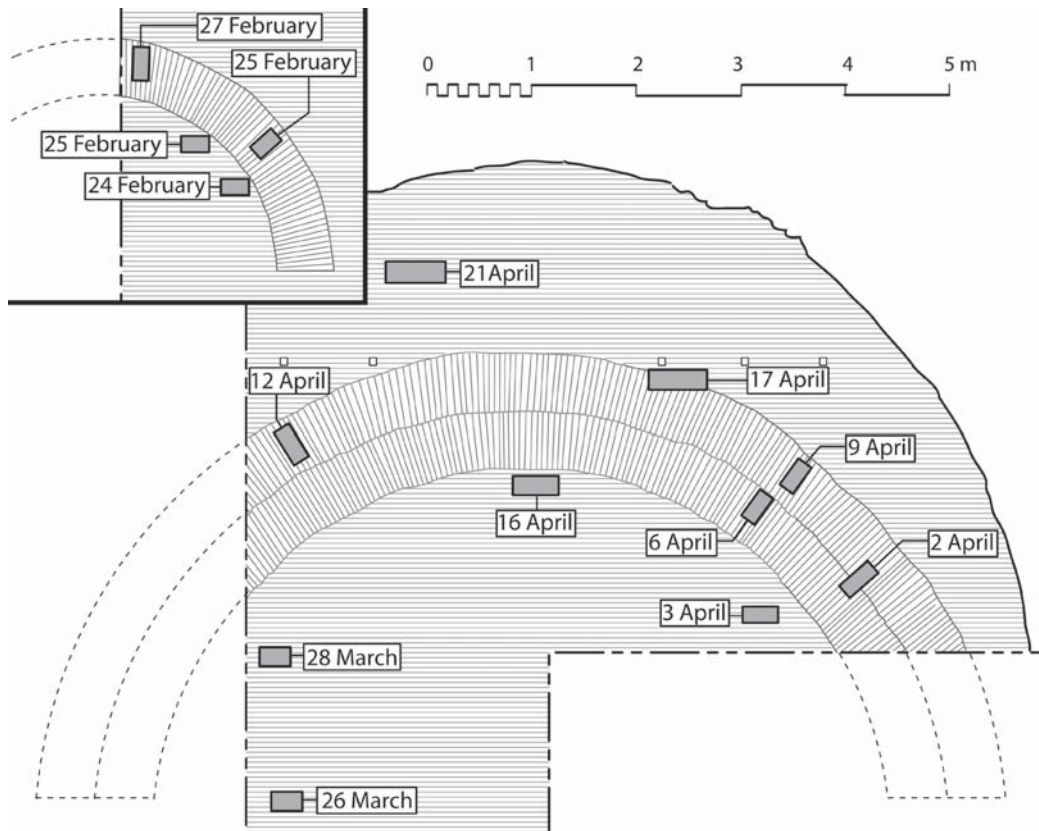


Fig. 4: Relieving arches from the cryptoporticus under Trajan's Baths (author's drawing based on Volpe 2002: figs. 3, 6, 10).

I now turn to another Trajanic structure, the latrine at the Forum of Caesar, which was added during the renovations that accompanied the construction of Trajan's Forum. It is very unusual in that it was built above earlier rooms rather than at ground level. The drainage, therefore, had to be incorporated between the vaults of the earlier rooms and the new latrine above. Moreover, the new latrine was built into a semi elliptical shape so that the walls did not align with the earlier parallel walls below it. To compensate for the lack of correspondence between the walls at the two levels the builders demolished the vaults of the earlier rooms and rebuilt them with a complex system of brick ribs, which corresponded to the ends of relieving arches in the new walls above (fig. 5). To help guide the loads to particular points within the structure the builders used

travertine springer blocks so that the relieving arches directed the loads onto the reinforced, ribbed sections of the barrel vaults (fig. 6). This is one of the most sophisticated surviving structures built before the Pantheon, and given the chronological proximity, the same people, both designers and builders, could have conceivably worked on both projects.

The structure of the Pantheon draws upon these earlier structural developments. The wall of the rotunda contains series of relieving arches at three levels. The lowest arches consist of only a single ring of bipedales whereas the upper ones are more substantial and consist of two or three rings of brick (either bipedales or sequipedales). The drawing in figure 7 shows a transparent view of the structure of this wall with the two upper series of brick relieving arches extending throughout the thickness of

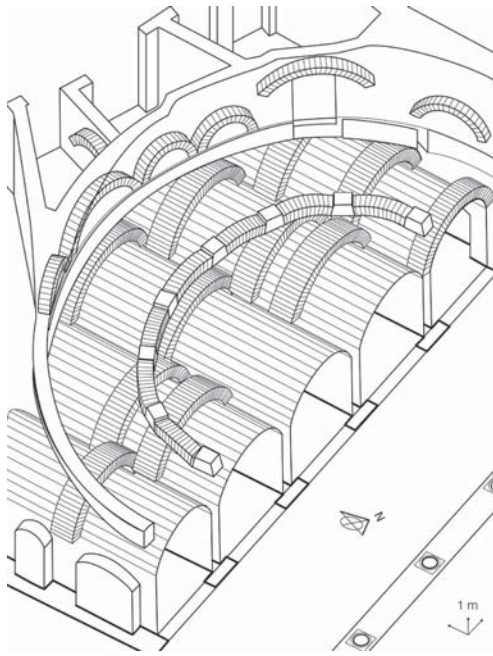


Fig. 5: Trajanic Latrine at the Forum of Caesar. Drawing of structural system comprising relieving arches and vaulting ribs.

the wall. Only the barrel vault over the entryway has a visible intrados revealing that it is built entirely of bipedales, thereby suggesting that the other barrel vaults in corresponding positions are constructed similarly. The nature of the relieving arches corresponding to the semidomes is less clear. Nevertheless, these arches were intended to direct the loads from the massive dome to the sides of the eight piers between the large interior niches. This is a much grander use of the brick ribs than at the latrine, but the latrine was clearly the practice ground for what was to come at the Pantheon.

The relieving arches in the Pantheon represent both of the intentions observed at the Domitianic Vestibule and at the Trajanic Latrine. An element common to the Trajanic Latrine and the Pantheon is the use of stone springer blocks to concentrate loads at particular points. At the Pantheon the springer blocks are used in conjunction with brick relieving arches to direct the load away from the architraves over

the columns of the niches (fig. 8). The use of the springer blocks at both monuments suggests that the intention was to channel point loads through the structure, whereas the large arches at the Pantheon (M on fig. 7) would have served both to direct loads to the eight piers and to consolidate the walls and protect against creep in the same way as those at the Domitianic Vestibule. In this sense, the Pantheon does represent the most advanced and sophisticated application of such arches.

I turn now to the use of lightweight caementa in the Pantheon dome. The use of concrete provided the builders a means of controlling the mass of a structure by using stones of different weights as caementa in different parts of the building. The section of the Pantheon in figure 8 shows the distribution of the different types of caementa used: from the heaviest (travertine) at the bottom to the lightest (volcanic scoria and yellow tuff) at the top. Notice, however, that the whole dome is not made as light as possible. Only the crown has the lightweight scoria and yellow tuff. This combination of stones was first used at the Baths of Trajan and at the Basilica Ulpia. Mineralogical analysis shows that the scoria in the Pantheon and that of the earlier Trajanic buildings all are products of Mount Vesuvius. It was evidently imported by ship because it has been found in one building at Ostia as well.⁴ This is one of the only non-decorative stones imported into Rome, and it only occurs in imperially sponsored buildings.

The Pantheon was obviously built after the great AD 79 explosion that destroyed Pompeii, but the scoria seems to have been an export item from Pompeii before the explosion. Vitruvius (*de Arch.* 2.6.2–3), writing towards the end of the first century BC, notes the existence of a sponge-like stone from Vesuvius that he calls *pumex pompeianus*, and this Vesuvian scoria must be the material to which he refers. In fact, it occurs used alone as caementa as early as the mid first century BC in vaults at the Fo-

4 Lancaster 2005, 66, 222–224.



Fig. 6: Trajanic Latrine at the Forum of Caesar. Photo of springer blocks directing loads to underlying vaulting ribs.

rum of Caesar.⁵ The scoria found in Pompeii was produced in a small explosion dating from around the 10th–9th century BC and underlies the city itself.⁶ The AD 79 explosion was much larger and covered much of the area where the scoria would have been quarried. Therefore, the scoria for the Trajanic buildings that use it and for the Pantheon had to be excavated from underneath the 79 deposits. The most accessible places would have been in the areas away from the coast where the 79 deposits were not so deep, but this would have been more expensive due to the cost of transport to the sea and to the fact that the port at Pompeii had been destroyed (fig. 9).

A comparison with the Mount St. Helens explosion in 1980 is enlightening because the event there was very similar, albeit smaller, to the 79 explosion of Vesuvius. At Mount St. Helens, the

event destroyed an old growth forest, unlike the area around Vesuvius which was largely tilled fields for vegetables and fruit trees. The rate of the recovery of the landscape around Mount St. Helens provides us with comparanda for the damage inflicted by pyroclastic flows: even twenty years later the recovery of the landscape is only minimal. Excavations and finds around Vesuvius confirm a similar situation for the area around Vesuvius. Hadrianic milestones indicate that the roads were only being rebuilt some 40 years later, and the 2nd-century burials found in the area tend to be low status, suggesting that this once fertile region took generations to recover economically.⁷ The Vesuvian scoria began to appear in imperial vaulted structures in Rome 20–25 years after the explosion, and I wonder if the idea to quarry the scoria for the vaults could have been part of an imperial initiative under Trajan to use the natural resources still available under the ground since the topsoil was not yet

⁵ Amici 1991, 52, 162.

⁶ Ranieri 1998, 135–141; Ranieri/Yokoyama 1997, 33–50; Kawamoto/Tatsumi 1992, 92–97.

⁷ Pagano 1995–1996, 35–39, fig. 1.

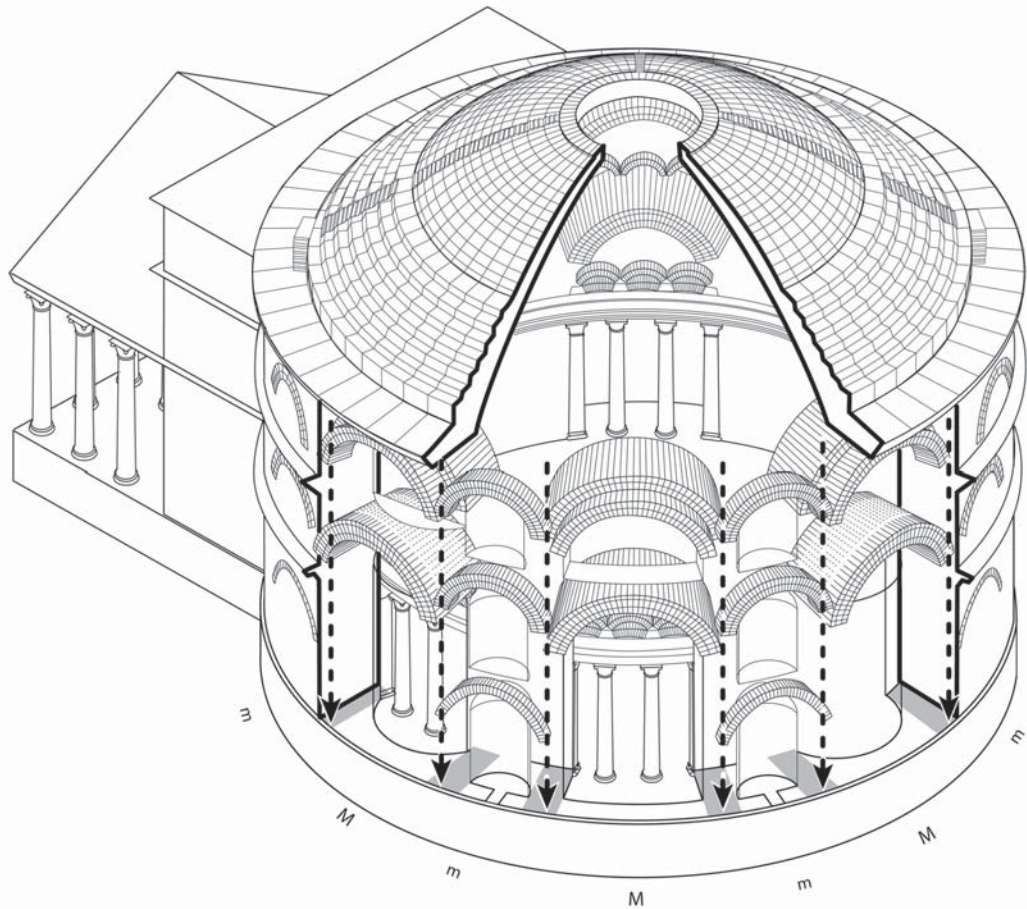


Fig. 7: Pantheon. Drawing of structural system of arches/ ribs in rotunda wall.

developed enough to sustain large-scale agriculture. In any case, the scoria was not a common phenomenon in Rome and clearly some effort by the imperial administration was put into excavating and shipping the material to Rome. Given the evident effort to acquire the scoria, one wonders whether its structural efficacy was worth it. To answer this question, I applied a thrust line analysis to a series of Pantheon models in which I substituted various weights of caementa in different parts of the dome (fig. 10). All the models are based on the assumption that the primary relieving arches/ribs do in fact concentrate the load onto the eight piers between the niches and that there is no hoop tension due to the cracks in the dome; therefore each model assumes that one

pier is carrying a 45° wedge of the dome, which is one eighth of the entire dome.

To test the effectiveness of the lightweight caementa in the crown of the vault, I manipulate the weight of the materials. Model P₃ was created by taking the existing vault as built (P₁) and substituting the heavier brick and tuff caementa used in the haunches with the lightweight caementa used in the crown to create an overall lighter dome. P₃ shows that making the whole dome lighter actually *increases* the lateral thrust slightly, though not significantly. In Model P₄, I make the entire dome heavier with the haunch material at the crown. This has a more significant effect on the thrust line, though it still does not cause failure. These tests show that the builders understood the importance of making

the crown as light as possible while keeping the haunch heavier in order to counteract the lateral thrusts. Simply making the whole dome light was not the best solution. However, the tests also suggest that the use of the Vesuvian scoria in the dome was not in fact a critical element in the stability of the structure in spite of the effort required to import it.

The final structural element I examine is the series of step-rings on the exterior of the dome. In the past, there have been two proposals for their purpose. One is that they were added to make the construction of the dome easier to build so that the exterior could be built in steps thus avoiding forming the curved extrados in the lower parts of the dome. The second is that they were intended to act as surcharge or extra weight over the haunch of the vault.⁸ In fact, some evidence from Trajan's Markets suggests that this second reason is more likely.

At the north end of Trajan's Markets are two semidomed rooms, the larger of which has an internal diameter of 17 m. On the exterior it was surrounded by a c. 1.3 m high step-ring, which is often cited as the precursor to the Pantheon step-rings. One side of the dome has been cut away revealing a section through the semidome that shows that the step-ring was added after the semidome was completed and cannot have been used to aid in its construction (fig. 11). A 15 cm layer of *cocciopesto* was applied to the extrados of the semidome before the step-ring was added. However, the step-ring itself has Trajanic brick stamps in the facing, so it was apparently built fairly soon after the semidome was finished.⁹ This example implies that the step-ring was added as a structural precaution and was not conceived as a constructional aid.

Finally, given this information I end with a thrust line analysis of the Pantheon dome comparing the effect of the step-rings to the use of lightweight caementa in the dome. The results of Model P5 in figure 10 show that the

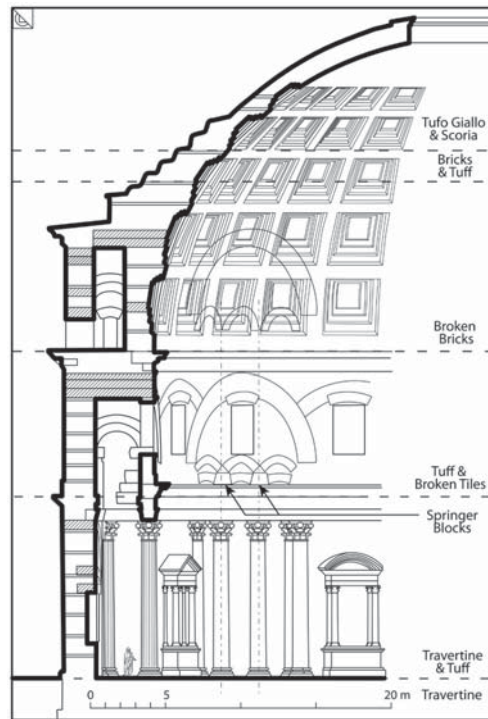


Fig. 8: Pantheon. Section showing distribution of caementa types and location of springer blocks.

elimination of the step-rings has a much more substantial effect on the thrust line, pushing it further outwards, though again not so far as to cause the structure to fail.

These thrust line models were inspired by the article of Robert Mark and Paul Hutchinson¹⁰ who used finite element modeling to calculate the stress levels in their various models. Thrust line analysis is somewhat different from finite element modeling in that it does not measure stress, which ultimately must be compared to known stresses of particular materials (which we often do not know); rather it provides a visual measure of stability based on the relationship between form and mass.¹¹ It is a method that comes closer to the way that the Roman builders were thinking, that is, in terms of «pushing out» or in Vitruvius's words «*extruderent*» (*de Arch.* 6.8.4).

8 MacDonald 1982, 110.

9 Lancaster 2000, 766–767.

10 Hutchinson/Mark 1986.

11 For further explanation, see Lancaster 2005, 158–161.

My intention in conducting the thrust line analyses was not to test the stability of the structure (as it still stands), but rather to test the *relative* effect of the weight distribution through the use of different weights of stone and added mass in the form of step-rings. The analyses ultimately demonstrate that the Roman builders had a very highly developed intuitive sense for the structural behavior of their buildings without any concept of internal stresses within material or any means of calculating thrust lines.

The Pantheon is indeed a marvel of constructional ingenuity, but it is the result of a century of experimentation with the use of advanced building elements such as the relieving arch, vaulting rib, lightweight caementa, and step-rings. Unique, however, is the way in which these pre-existing elements were combined into a structural system that has allowed the largest unreinforced concrete dome ever built to stand for almost two millennia.

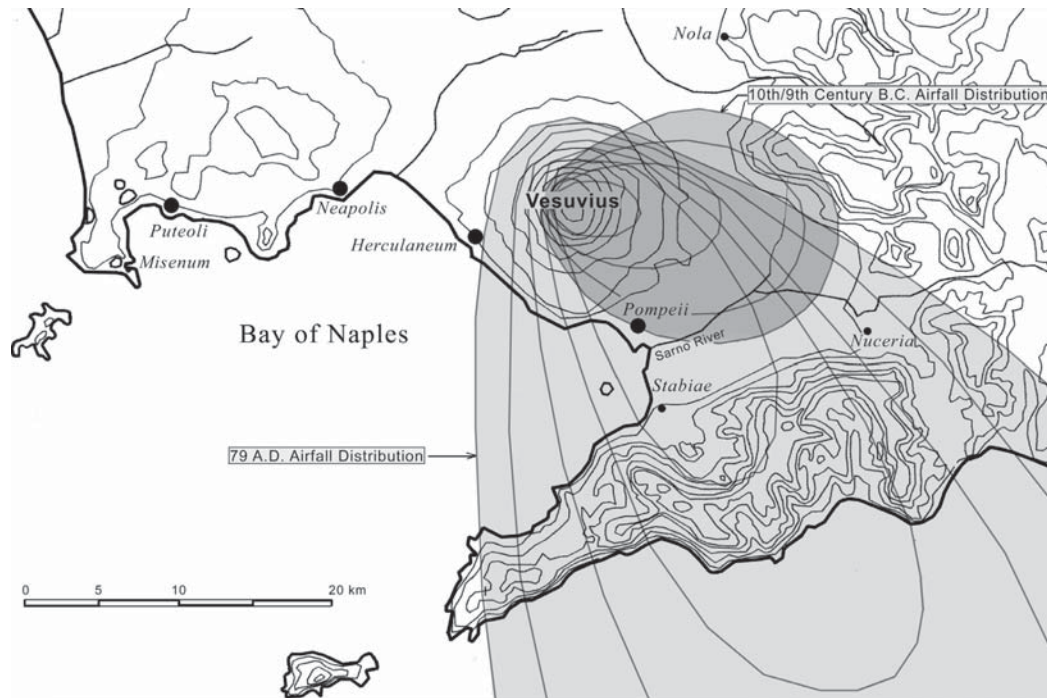


Fig. 9: Map of Bay of Naples showing the distribution of fallout from the 10th-9th century BC eruption compared to that of the AD 79 eruption.

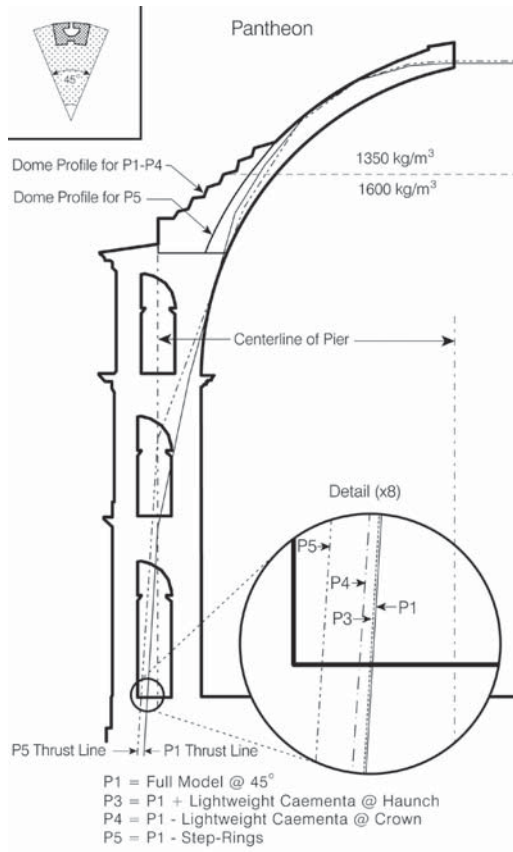


Fig. 10: Pantheon. Results of thrust line analysis.



Fig. 11: Trajan's Markets. Step-ring on extrados of the semidome at the north end of hemicycle.