The Principal Design Methods for Greek Doric Temples and their Modification for the Parthenon

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INTRODUCTION

During the fifth century B.C., Greek architects perfected a method for designing Doric peripteral temples, and this procedure was used for most temples constructed during the second half of the century in mainland Greece and in its colonies. This procedure had to be determined in order to see how it was adapted to design the Parthenon. Minor modifications enabled the architects of the Parthenon to achieve greater commensurability than for any other Doric temple (Fig. 1).

To lay foundations for a Doric temple, an architect needed to know the number of columns and the overall length. Since nearly all peripteral temples of the Doric Order

Fig. 1. *Parthenon*, c. 1875 *(Anon.; author)*

have six columns on their fronts, the first decision which ordinarily needed to be made was how many columns would be used on the sides, and for hexastyle temples this ranged from ten to sixteen columns. The ratio of the number of columns on the fronts to the number on the sides determined the overall form and was the single most important ratio which had to be selected. The column number ratio was reused as the ratio for the stylobate of some of the earliest stone temples (Table 1, column 2; Table 2, column 6), and it was later applied to the krepis. It was used as the ratio of the krepis for the great majority of temples constructed from *c.* 535 and *c.* 320 (Table 1, column 1; Table 2, column 4).

Another procedure for the design of later temples was the use of a regularly proportioned frieze. This made it possible to determine where columns would need to be placed so that every other triglyph would eventually be centred above a column except at the corners of the frieze. The standard frieze became possible as soon as metopes were made one-and-a-half times the width of triglyphs and began to relate to one another as 2:3 in the way Vitruvius described. Nearly all Doric temples constructed from *c.* 495–*c.* 320 have interaxials equivalent in length to the width of five triglyphs (Table 1, column 3; Table 3, column 7).

TABLE 1. APPLICATION OF RATIOS TO DORIC TEMPLES WITHIN 2 PER CENT OF PREDICTED AMOUNTS

Abbreviations:
AX = interaxial, CH = column height, col. # = column number, EH = entablature height, K = krepis, LD = lower diameter, OH = order height, S = stylobate, T = triglyph, X = presence of a characteristic. Explanations: (1) col# = K—The number of columns for fronts to sides have the same proportion as the width to the length of the krepis. (2) col.# = S—The number of columns for fronts to sides have the same proportion as the width to length of the stylobate. (3) T:AX::1:5—The triglyph to interaxial ratio is as 1:5. (4) T:LD::1:2—The triglyph to lower diameter is as 1:2. (5) AX:CH::1:2—The interaxial to column height is as 1:2. (6) LD:AX ::1:2.5—The lower diameter to interaxial as 1:2.5. (7) AX:OH::1:3—The interaxial to order height is as1:3. (8) EH:OH::1:4—The entablature height to order height is as 1:4. (9) T:K::T#—The triglyph width to krepis length is equal to the length of the krepis divided by the number of columns times 5.

Name, Place	(1) col.# =K	(2) col.# =S	(3) T:AX ::1:5	(4) T:LD ::1:2	(5) AX:CH 1:2	(6) LD:AX ::1:2.5	(7) AX:OH ::1:3	(8) EH:OH ::1:4	(9) T:K :T#
1. Heraeum, Olympia		X							
2. Apollo, Syracuse									
3. Olympieion, Syracuse		X		X					
4. C, Selinous					X		X		
5. Athena, Assos		X			X				
6. Apollo, Corinth		X							
7. D, Selinous	X								
8. Hera I (Basilica), Paestum									
9. FS, Selinous	X				X	X			
10. Athena Polias, Athens	X	X		X		X	X		
11. GT, Selinous	X		X						X

Name, Place	(1) col.# =K	(2) col.# =S	(3) T:AX ::1:5	(4) T:LD ::1:2	(5) AX:CH 1:2	(6) LD:AX ::1:2.5	(7) AX:OH ::1:3	(8) EH:OH ::1:4	(9) T:K :T#
12. Olympieion, Akragas	X								
13. Athena (Ceres), Paestum	X								
14. Tavole Pal., Metapontion	X								
15. A (Hercules), Akragas							X		
16. Athena Pronaia, Delphi	X			X		X			
17. Poseidon I, Sunion	X					X			
18. Aphaia, Aigina	X		X	X	X				X
19. Older Parthenon, Athens	X							X	
20. Athena, Syracuse	X		X				X		
21. Nike, Himera	X		X						X
22. ER (Hera), Selinous	X		X						X
23. Zeus, Olympia	X		X		X				
24. Hera II (Posei.), Paestum	X		X		X				X
25. Hera Lacinia, Akragas			X		X		X		X
26. A, Selinous							X		
27. Apollo, Bassai	X		X				X	X	X
28. Hephaisteion, Athens	X		X	X		X	X	X	X
29. Parthenon, Athens	X							X	X
30. Poseidon II, Sunion	X		X					X	X
31. Ares, Athens	X			X		X	X	X	
32. Nemesis, Rhamnous	X		X					X	X
33. Concord, Akragas	X		X				X		X
34. Segesta	X						X		
35. Hera, Argive Heraion	X		X	X		X	X	X	X
36. Asklepios, Epidauros	X						X		X
37. Apollo, Delphi	X		X						X
38. Athena Alea, Tegea	X		X						X
39. Zeus, Nemea	X								X
40. Zeus, Stratos	X								X
41. Metroön, Olympia	X		X						X
42. Apollo II, Delos	X			X					
43. Athena Pol., Pergamon									

The key to how most Doric temples were designed is that the width of a triglyph could be determined from the length of the krepis. The needed dimensions for the trigyph of a temple of any size or shape could be determined by multiplying the number of columns times five and dividing the product into the length. For example, 13 columns times 5 is 65 modules, and if a temple were made 100 Doric feet long, the size the triglyph needed could be readily determined by dividing 100 feet by 65 modules. In this example, the result is 1.54 feet, but the closest this could be measured was 1 Doric foot and somewhat less than 9 dactyls. An approximation of the needed fraction of a dactyl sufficed. So long as identically the same measurement was used repeatedly, the overall size would be close to 100 Doric feet, and all elements of the building would be accurately proportioned to one another. By marking off a length equal to five triglyphs, an architect could determine exactly how far apart most columns would need to be placed so that they would later align with the frieze. Corner columns were placed in residual space at each corner of the stylobate.

More than two centuries ago, Stuart and Revett made measured drawing of the Hephaisteion showing that some of its krepis blocks aligned with the centres of columns and with the centres of alternate triglyphs (Fig. 2).[1] A drawing by Balanos shows that the Parthenon's columns are centred over joints in the top and bottom levels of the krepis (Fig. 3).[2] For the frieze to align with the krepis on all four sides, it is evident that the entire design of these temples had to have been worked out before the blocks of the krepis were cut to fit their intended locations and even before the foundation trenches were dug.

Scholars who have made a special study of design of all Doric temples have generally taken for granted that the plan was worked out at the level of the stylobate rather than at the level of the enthynteria. William Bell Dinsmoor was so convinced that he included measurements for the stylobate, but not for the krepis in his comprehensive tables of dimensions and proportions for Doric temples.[3] J. J. Coulton recognized that for seventeen temples the column number ratio was applied to the krepis, and he revised and augmented Dinsmoor's data, including available dimensions for each triglyph and krepis.[4]

Any explanation of how Doric temples were designed must explain how exact dimensions were determined for the krepis blocks before construction began. It must reconstruct a sequence capable of generating the measurements which actually exist. In this article the principal dimensions of two buildings will be accounted for to show that they were designed using procedures which developed early and continued to be used despite continuing advances in Greek mathematics.[5]

DESIGN PROCEDURES RECOMMENDED BY VITRUVIUS FOR DORIC TEMPLES

Since Roman Doric temples were influenced by Tuscan temples, they were given a podium rather than a krepis; their columns were placed on the front rather than around the entire perimeter; they were planned using intercolumniations rather than interaxials; and they had a broader intercolumniation in the centre rather than narrower interaxials at each end. In his attempt to apply the design conventions of the Greek Doric temple to the Tuscan temple, Vitruvius had to ignore some as wholly incompatible and to adapt others. Even so, his recommendations provide important insights into how Greek Doric temples were designed.

Vitruvius stated that he based his design procedure for a Roman Doric temple (Fig. 4) primarily on intercolumniations and that he worked out his plan on the stylobate.[6] To maintain the proportions of the relatively thin frieze and wide intercolumniations of the Tuscan temple, he inserted an extra triglyph and metope into each intercolumniation and yet another triglyph and metope for the still wider central

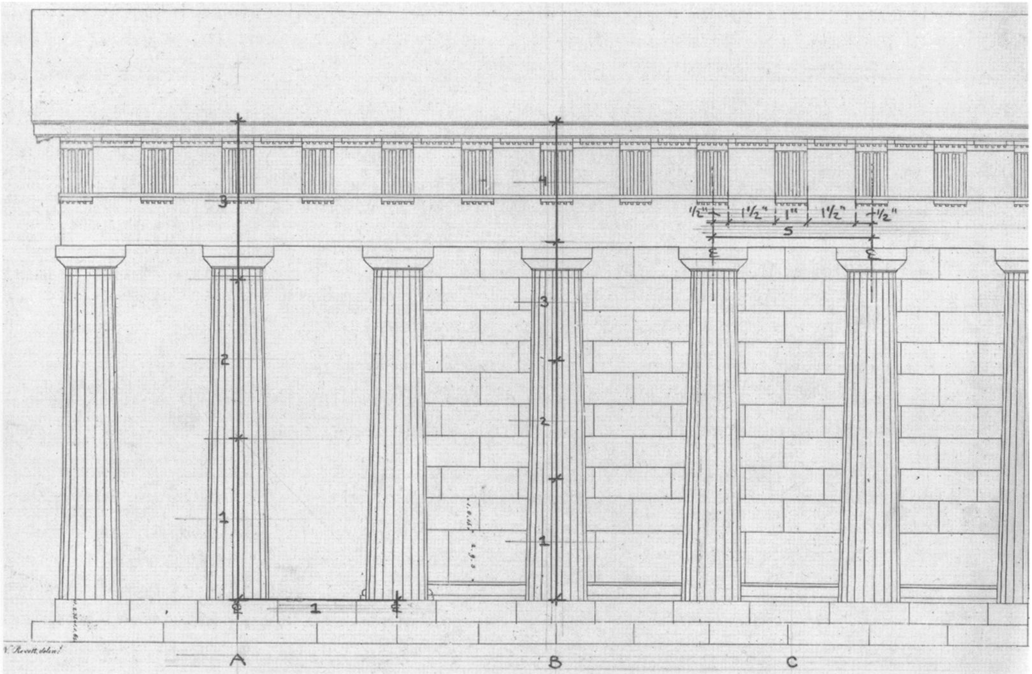

Fig. 2. *Partial elevation of the peristyle of the Hephaisteion by Stuart and Revett* (Antiquities of Athens, 3, *ch.* 1, *pl.* 10; *detail annotated by author)*

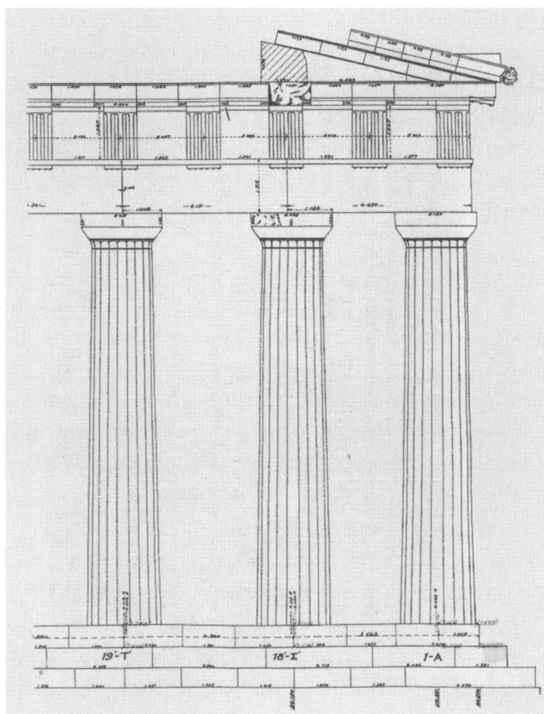

Fig. 3. *Partial elevation of the peristyle of the Parthenon by Balanos* (Les Monuments de l'Acropole, *drawing no.* 10; *detail)*

opening. Despite these major differences, he retained the Greek ratio of 2:3 for triglyph to metope. However, by making his columns two modules in diameter, he was able to plan his stylobate in a way similar to the one he described, using the lower diameter of a column as the module to design Ionic and Corinthian temples. He then needed only to count off modules to determine where columns would be placed regardless of which of the three principal orders was chosen.

How much Vitruvius borrowed from Greek sources and how much he changed can be determined by checking each of his recommendations to see how well it fits surviving Greek temples such as the Hephaisteion (Fig. 5). Some recommendations fit with precision, and the ones which do not can be disregarded as an attempt to create a design method for a Roman Doric temple similar to the procedure he outlined for Roman Ionic and Corinthian temples.

Vitruvius (1.2.4) provides an essential clue for determining how Greek Doric temples were designed by stating that any element of a temple might be used as a module and by specifically mentioning the triglyph as an element which could be used to achieve commensurability.[7] The great advantage in using a triglyph as a module for Greek Doric architecture was that once the width of a triglyph was determined, no further computations were necessary to determine the location of all columns.

Vitruvius (4.3.4-8) describes in detail how triglyphs could be used to lay out the front of a Roman Doric temple. He states that he is using lower column diameters for planning purposes, but his computations are based on modules which are half of a column diameter. He notes that a triglyph is one module wide, and thus the triglyph is actually his module. Even though his column diameter was two modules wide, he used it as if it were the actual module to make his method consistent with Greek and Roman design practices for the Ionic Order (3.2.6; 3.3.3). For example, Dinsmoor noted that the interaxial of the Ionic Temple of Athena Nike, Athens, is 2.99 column-diameters wide and that the Corinthian Temple of Zeus, Euromus, has an interaxial 3 column-diameters wide, and in both cases the intercolumniations are 2 column-diameters wide. This simple method for planning an Ionic or Corinthian temple is not fully compatible with a regular Greek Doric frieze, and when a conflict arose, Vitruvius reverted to the triglyph.[8] However, he disregarded the invariable Greek rule of placing triglyphs at each corner, and he solved the corner problem to his satisfaction by centring end triglyphs over end columns and leaving the corners of the frieze blank (Fig. 3).

Vitruvius evidently adopted a number of Greek Doric proportional relationships which had been used to design temples such as the Hephaisteion. For example:

(1) For the lower diameter of columns, he recommended a width of two triglyph-modules. The usual triglyph width for the Hephaisteion is 0.515 m, and twice this is 1.03 m. The actual width of the lower diameter is 1.018 m (1.2 cm less; 1.2 per cent discrepancy).

(2) For the metope, he recommended 1.5 modules or 0.773 m, and the actual width is usually 0.775 m (2 mm more; 0.3 per cent discrepancy).

(3) For the capital width, he recommended 2.17 modules ($2\frac{1}{6}$), which would be 1.118 m, and the actual width of the abacus is 1.14 m (2.2 cm more; 1.9 per cent discrepancy).[9]

Although most of the proportions recommended by Vitruvius were not followed in

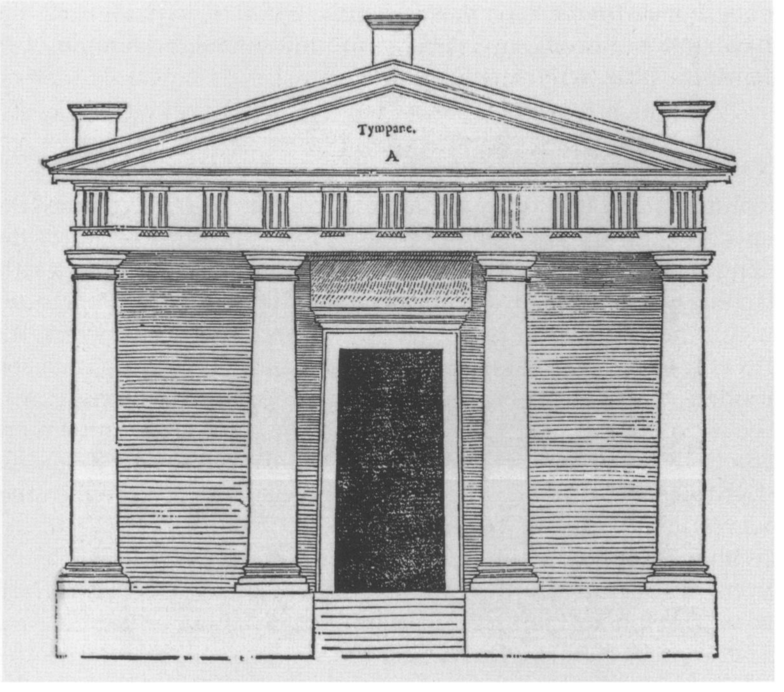

Fig. 4. *Vitruvius' Doric order reconstructed by Serlio* (Five Books of Architecture *[New York, 1982 repr. of 1611 edn], bk 4, ch. 6, fol. 19; detail)*

Fig. 5. *Hephaisteion,* c. 1880 *(Anon.; author)*

the Hephaisteion, enough measurements are sufficiently close to indicate that the architect of the Hephaisteion was using triglyphs as modules, and the temple itself provides further evidence that this was the case.

DESIGN OF THE HEPHAISTEION

The Hephaisteion's column number ratio for 6 by 13 columns is 1:2.17, and the dimensions of its krepis also relate to one another as 1:2.17.[10] Since the length of the krepis is 33.48 m, the length simply needed to be divided by 2.17 times to get the width. The width computed in this way is 15.43 m, and the actual width is 15.42 m (1 cm more; 0.1 per cent discrepancy).[11] Since 33.48 m is 102 Doric feet and about 11 dactyls, the intended overall length of the temple is likely to have been 100 Doric feet, a dimension which a number of other temples closely approximated. After the module was measured as accurately as possible, it seems to have been slightly too large, but a more important consideration in this case than an exact overall length was having a module of approximately the right size that could be applied with precision to achieve the most important proportional relationships.

The width of a triglyph was found by dividing the overall length by 65 triglyphs (13 columns times 5 triglyphs). The actual length of 33.48 m divided by 65 is 0.515 m, which is the actual width of a trigylph to the nearest millimetre. Knowing what size the triglyph needed to be, he could be certain when he laid the krepis blocks that the centres of the columns and alternate triglyphs would align if the temple were constructed accurately (Fig. 2c). The fronts were planned similarly, and after the foundations were constructed and levelled, a highly accurate plan could be marked on the euthynteria at full scale.

The architect knew his frieze would ordinarily be equivalent to 61 triglyphs in length (with the equivalent width of 5 triglyphs planned for each of the 12 interaxials plus a half-triglyph added to each end). The computed length for 61 triglyphs is 31.415 m, and the actual length for the frieze is 31.546 m (13.1 cm more; 0.4 per cent discrepancy). The steps on all four sides are 1.71 m wide, and since the krepis corresponds with precision to the column number ratio, it is evident that the steps were deducted from the krepis to determine the size of the stylobate (13.708 m by 31.769 m). As a result, the stylobate has the arbitrary ratio of 1:2.32. Since the rows of columns align with the edge of the stylobate and since every regular column aligns with an alternate triglyph, the positions of all but the corner columns were fixed by the steps in relation to the krepis, and the corner columns necessarily had to be placed on axis with the adjacent rows of columns. There was consequently no way calculations could have been used to adjust the position of the corner columns for visual effect. Since there was no way to measure calculations which resulted in measurements of less than a dactyl, precise calculations for contractions could not have been applied accurately.

Vitruvius (4.3.2) states that contractions were a fault. If contractions had been considered a visual improvement, their use would not have been confined to Greek Doric temples. They were a less conspicuous and more acceptable fault than metopes, which differed greatly from one another in size and shape, and the creation of a regular frieze took precedence.

TABLE 2. PROPORTIONS OF COLUMN NUMBER TO KREPIS AND STYLOBATE

Abbreviations:
col. # = column number, K = krepis, L = length, S = stylobate, W = width, * = Coulton's 17 temples with col. # = K within 1%.

Explanations:
(1) col.#—Number of columns on fronts by number of columns on sides (counting corner columns twice).
(2) col.# W:L—Column number ratio for sides with fronts equal to 1.
(3) K W:L—Ratio for krepis length with width equal to 1.
(4) % col.# ÷K—Percentage of column number ratio divided by krepis ratio.
(5) S W:L—Ratio for length of stylobate with width equal to 1.
(6) % col.# ÷S— Percentage of column number ratio divided by stylobate ratio.

Name, Place	Date	(1) col.#	(2) col.# W:L	(3) K W:L	(4) % col. # ÷ K	(5) S W:L	(6) % col. # ÷ S
1. Heraeum, Olympia	c. 590	6x16	2.67	2.54	+5	2.67	0.0
2. Apollo, Syracuse	c. 565	6x17	2.83	2.38	+19	2.57	+10
3. Olympieion, Syracuse	c. 555	6x17	2.83	2.56	+11	2.77	+2.2
4. C, Selinous	c. 550-530	6x17	2.83	2.70	+5	2.66	+6
5. Athena, Assos	c. 540	6x13	2.17	2.08	+4	2.16	+0.5
6. Apollo, Corinth	c. 540	6x15	2.50	—	—	2.51	-0.4
7. D, Selinous	c. 535	6x13	2.17	2.13	+1.8	2.36	-8
8. Hera I (Basilica), Paestum	c. 530	9x18	2.00	2.15	-7	2.21	-10
9. FS, Selinous	c. 525	6x14	2.33	2.32	+0.4*	2.54	-8
10. Athena Polias, Athens	c. 529-515	6x12	2.00	2.01	-0.5*	2.03	-1.5
11. GT, Selinous	c. 520-450	8x17	2.13	2.13	0.0*	2.20	-3
12. Olympieion, Akragas	c. 510-409	7x14	2.0	2.02	-1.0*	2.09	-4
13. Athena (Ceres), Paestum	c. 510	6x13	2.17	2.14	+1.4	2.26	-4
14. Tavole Pal., Metapontion	c. 500	6x12	2.00	2.00	0.0*	2.08	-4
15. A (Heracles), Akragas	c. 500	6x15	2.50	2.72	-8	2.65	-6
16. Athena Pronaia, Delphi	c. 500	6x12	2.00	2.00	0.0*	2.07	-3
17. Poseidon I, Sunion	498	6x13	2.17	2.19	-1.1	2.31	-6
18. Aphaia, Aigina	c. 495-485	6x12	2.00	1.97	+1.5	2.09	-4
19. Older Parthenon, Athens	488-480	6x16	2.67	2.66	+0.4*	2.84	-6
20. Athena, Syracuse	480	6x14	2.33	2.38	-2.1	2.50	-7
21. Nike, Himera	480	6x14	2.33	2.34	-0.4*	2.49	-6
22. ER, Selinous	c. 480-460	6x15	2.50	2.56	-2.3	2.67	-6
23. Zeus, Olympia	468-460	6x13	2.17	2.21	-1.9	2.32	-6
24. Hera II (Poseidon), Paestum	c. 460	6x14	2.33	2.37	-1.7	2.47	-6
25. Hera Lacinia, Akragas	c. 460	6x13	2.17	2.07	+5	2.25	-4
26. A, Selinous	c. 460	6x14	2.33	2.75	-15	2.50	-7
27. Apollo, Bassai	c. 450-425	6x15	2.50	2.50	0.0*	2.64	-5
28. Hephaisteion, Athens	449-444	6x13	2.17	2.17	0.0*	2.32	-6
29. Parthenon, Athens	447-432	8x17	2.13	2.15	-0.9	2.25	-5
30. Poseidon II, Sunion	444-440	6x13	2.17	2.16	+0.5*	2.31	-6
31. Ares, Athens	440-436	6x13	2.17	2.16	+0.5*	2.31	-6

Name, Place	Date	(1) col.#	(2) col.# W:L	(3) K W:L	(4) % col. # ÷ K	(5) S W:L	(6) % col. # ÷ S
32. Nemesis, Rhamnous	436-432	6x12	2.00	1.97	+1.5*	2.13	-7
33. Concord, Akragas	c. 430	6x13	2.17	2.14	+1.4	2.33	-7
34. Segesta	424-416	6x14	2.33	2.33	0.0*	2.51	-7
35. Hera, Argive Heraion	423-416	6x12	2.00	1.97	+1.5	2.13	-6
36. Asklepios, Epidauros	c. 380	6x11	1.83	1.85	-1.1	1.94	-6
37. Apollo, Delphi	366-326	6x15	2.50	2.53	-1.2	2.68	-7
38. Athena Alea, Tegea	c. 350	6x14	2.33	2.34	-0.4*	2.48	-6
39. Zeus, Nemea	c. 340	6x12	2.00	2.01	-0.5	2.13	-6
40. Zeus, Stratos	c. 321	6x11	1.83	1.86	-1.6	1.96	-7
41. Metroön, Olympia	c. 320	6x11	1.83	1.82	+0.5*	1.95	-6
42. Apollo II, Delos	c. 460-280	6x13	2.17	2.17	0.0*	2.29	-5
43. Athena Polias, Pergamon	c. 250	6x10	1.67	1.73	-3	1.77	-6

The frieze is 11.15 cm shorter at each end than the stylobate, but the stylobate needed to be slightly longer to allow for a small projection beyond the base of the columns and for the inward lean of the columns.[12] Despite the inward lean, the base of columns remained on centre, and the position for the base of every column except the corner columns could still be established by counting modules.

Modules the width of a triglyph were used extensively in the design of the Hephaisteion. They were counted to determine the width of metopes (1.5), the height of metopes and triglyphs (1.5), the lower diameter of columns (2), the width of the usual interaxial (5), the overall width of the frieze (26), the overall length of the frieze (61), the width of the krepis (30), and the length of the krepis (65).

The amount of error increased as construction progressed. Since each column had to lean inward and since its base had to be cut to fit a curving stylobate, minor errors inevitably occurred in fitting the bases of columns to the stylobate, and the amount of these errors was magnified at the top of the columns. Increasingly different widths for the interaxials had to be compensated for at each level, but this was easily done since every stone was cut by hand to fit. At the level of the stylobate, the curves were only 2.7 cm on the fronts and 3.4 cm on the sides, but the same curve had been given to each level of the krepis, and the curve was also reflected in the entablature.[13]

The order height is almost three interaxials (15 modules) tall: 2.58 m times 3 equals 7.74 m, and the actual order heights are 7.73 m on the front and, including the cyma, 7.69 m on the sides (1 mm and 5 mm smaller; 0.01 and 0.1 discrepancy; Fig. 2A).[14] Between *c.* 550 and *c.* 380, at least thirteen temples had their order height determined by using three interaxials (Table 1, column 7).

When the column height of 5.71 m is divided by the order height, the column is 74 per cent of the order height or approximately three-quarters. This left 26 per cent or approximately one-quarter for the entablature. Neither the column height nor the entablature height are multiples of an interaxial (2.58 m) or of a triglyph (0.515 m), but, instead, relate to one another as 3:4 and 1:4 (Fig. 2B). This ratio was probably introduced

TABLE 3. RATIO OF TRIGLYPH WIDTH TO KREPIS LENGTH FOR ALL TEMPLES CONSTRUCTED FROM *c.* 450-*c.* 320

Abbreviations:
Col.# = column number, T = triglyph, X = presence of characteristic.
Explanations:
Krepis length in m—Overall length of krepis in metres.
Col. #— Number of columns along the sides.
Col.# ? 5T—Number of side columns times 5 triglyphs.
Predicted T width in m—Overall length of krepis divided by number of side columns times 5.
Actual width in m—Average actual width of triglyphs in metres.
Predicted - actual in mm—Predicted triglyph width minus actual triglyph width in millimetres.
% discrepancy—Percentage of difference between predicted triglyph width and actual triglyph width.
(8) X<2%—Presence of an 'X' in this column indicates that the difference between the predicted triglyph width and actual triglyph width is less than the 2 per cent margin allowed for all types of errors.

Temple, Place	(1) Krepis length in m	(2) Col. #	(3) Col. # x5T	(4) Predicted T width in m	(5) Actual T width in m	(6) Predicted -actual in mm	(7) % discre-pancy	(8) X <2%
27. Apollo, Bassai	39.57	15	75	0.528	0.536	-8	1.5	X
28. Hephaisteion, Athens	33.48	13	65	0.515	0.515	0	0.0	X
29. Parthenon, Athens	72.32	17	85	0.851	0.841	10	1.2	X
30. Poseidon II, Sunion	32.8	13	65	0.505	0.51	-5	1.0	X
31. Ares, Athens	35.032	13	65	0.539	0.554	-15	2.7	—
32. Nemesis, Rhamnous	22.76	12	60	0.379	0.377	-2	0.5	X
33. Concord, Akragas	41.99	13	65	0.646	0.64	-6	0.9	X
34. Segesta	61.17	14	70	0.874	0.85	24	2.8	—
35. Hera, Argive Heraion	39.60	12	60	0.66	0.65	10	1.5	X
36. Asklepios, Epidauros	24.45	11	55	0.445	0.441	4	0.9	X
37. Apollo, Delphi	60.32	15	75	0.804	0.82	-16	1.95	X
38. Athena Alea, Tegea	49.56	14	70	0.708	0.71	-2	0.3	X
39. Zeus, Nemea	44.221	12	60	0.737	0.730	7	1.0	X
40. Zeus, Stratos	34.12	11	55	0.620	0.625	-5	0.8	X
41. Metroön, Olympia	21.88	11	55	0.398	0.405	-7	1.7	X

by Iktinos at the Temple of Apollo, Bassai, in *c.* 450, but may have been used for the first time for the Hephaisteion. The same ratio was used for seven out of the nine Doric temples constructed from *c.* 450 to *c.* 380 (Table 2, column 8).

PRINCIPAL DESIGN METHODS FOR DORIC TEMPLES

Greek Doric architects adopted basic design procedures in the sixth century and continued to use them throughout the fifth century and well into the fourth century at sites on the Greek mainland and in Greek colonies. In 84 per cent of the 43 temples for which comprehensive measurements are available, the overall proportions were determined by applying the column number ratio either to the krepis or to the stylobate (Table 1, columns 1 and 2; cf. Appendix). The column number ratio determined the relative width to length of the krepis in 74 per cent of the examples (Table 1, column 1). For the period from *c.* 535-*c.* 320, the column number ratio was used to determine the krepis ratio in 89 per cent of the 36 temples built and so in nearly nine out of every ten cases (Table 2, column 4). The column number ratio was applied to the krepis with an accuracy of within one-half of 1 per cent for 14 temples and was applied to a total 32 temples with an accuracy of within 2 per cent (Appendix).

The column number ratio was applied to the stylobate in 9 per cent of the temples considered (Table 1, column 2). The 16 per cent of the temples which did not apply the column number ratio to either the stylobate or krepis were usually given interaxials in whole numbers of Doric feet, and the number of interaxials determined the proportions and overall dimensions.[15]

The kinds of experimentation characteristic of sixth-century temples virtually stopped at the beginning of the fifth century after a regular frieze equivalent to 5 triglyphs per interaxial was introduced at the Temple of Aphaia, Aigina (with its sides having the ratio of 1:5.07 and its fronts 1:5.18). Afterwards, the corner problem was solved as well as it could be by accepting contractions as an inevitable consequence of the framework of a regular frieze. From *c.* 450-*c.* 320 B.C., 87 per cent of all temples for which measurements are available have triglyph with widths within 2 per cent of predictable dimensions (Table 3).[16]

Interaxial length determined order height in 48 per cent of the 31 temples for which an order height can be determined (Table 1, column 7). During the period from *c.* 460-*c.* 380, nine of the twelve temples built or 75 per cent had an order which was 3 interaxials high (that is, 15 modules high). In seven of the same twelve examples, the entablature was made one-quarter and the column three-quarters of the order height (Table 1, column 8).

Although the interaxials for the fronts and sides of the Hephaisteion are identical in width, interaxials were measurably different on about three-quarters of all temples (Appendix). Even the interaxials of the Parthenon differ slightly, but consistently. Most earlier Greek temples had front and side interaxials which were substantially different, and this difference was made necessary by the imposition of a preferred ratio for the stylobate, krepis, or both. In the case of Hera I, Paestum, triglyphs of the same width were used for fronts and sides, and the difference in interaxials was made up by varying the widths of metopes on the fronts and sides.[17]

There are good reasons for believing that the great majority of Doric peripteral temples were designed using a procedure closely similar to the one described for the Hephaisteion and that, even before the frieze became regular, the columns number ratio was applied to the krepis (Table 1, column 1). The best evidence is the series of seven temples which had 6 x 12 columns and thus a column number ratio of 1:2. This was manifestly what was done for the krepis of the following 6 x 12-columned temples:

Athena Polias, Athens (*c.* 529-515): 1:2.01
'Tavole Paladine', Metapontion (*c.* 500): 1:2.00
Athena Pronaia, Delphi (*c.* 500): 1:2.00
Aphaia, Aigina (*c.* 495-485): 1:1.97
Nemesis, Rhamnous (*c.* 436-432): 1:1.97
Hera, Argive Heraion (423-416): 1:1.97
Zeus, Nemea (*c.* 340): 2.01

In all seven examples, the column number ratio was applied to the krepis within 2 per cent of one another. In four examples it was applied within 1 per cent, and in two of these four, it was applied with an accuracy of within 0.5 per cent. These temples were constructed between *c.* 529 and *c.* 340 B.C. and are located throughout the Greek World, and their similarities cannot be coincidental. To this list could be added the Olympieion, Akragas, which had 7 x 14 columns, a column number ratio of 1:2, and a krepis ratio of 1:2.02.

It might be argued that the krepis ratio was used to determine the column number ratio, but the ratio of 1:2 can equally produce the column numbers of 6 x 12, 7 x 14, and even 9 x 18 (Hera I, Paestum, which has the significantly different krepis ratio of 1:2.15). It is also unlikely that fractional ratios which divide out to irrational numbers generated an even number of columns. For example, 11 temples with 6 x 13 columns have the column number ratio of $2\frac{1}{6}$(2.166...), and seven temples with 6 x 14 columns have the column number ratio of $2\frac{1}{3}$(2.333 ...). The column number ratio was unquestionably the starting point in the design process for all of these temples.

This series of 6 x 12 temples is also important for showing which types of consequences were acceptable and which were not. Only one of the seven temples had the column number ratio applied to its stylobate as well as to its krepis: Athena Polias, Athens, which has a krepis ratio of 1:2.01 and a stylobate ratio of 1:2.03. This was the temple built by the Pesistratids from *c.* 529-515 and placed near the centre of the Acropolis. Although it was largely destroyed by the Persians in 480 B.C., its foundation survives, and many of its elements have been found in the north wall of the Acropolis. A consequence of applying the same ratio to both its krepis and its stylobate was necessarily that the steps would be unequal in size, and the reason is familiar to anyone who has planned the placement of a block of text on a printed page. If the text and page have the same proportions, the margins will differ in size. The actual dimensions of the front steps of Athena Polias are 27.5 cm wide, and its side steps are 40 cm wide (12.5 cm wider; 45.5 per cent discrepancy). If no ratio had been applied to either the krepis or stylobate or if a ratio had been applied only to the stylobate, steps of equal size could have been added to all four sides. Hera I, Paestum did not have its column number ratio applied to its krepis, and it has steps which are almost exactly equal on all four sides (5 mm different; 0.3 per cent discrepancy). The other six temples with 6 x 12 columns had steps which in chronological order differ from one another in percentages as 4.7, 1.4, 2.7, 18.2, and *c.* 3.1. The differences would probably have been unnoticeable except in a single instance.

In some cases it might be argued that the column numbers were generated by the proportions of the cella, but this cannot have been the case with the seven temples which have 6 x 12 columns. Even though they have nearly the same krepis ratio, their cella ratios vary substantially. The range for the ratios of the krepis of these temples is only from 1:1.97 to 1:2.01 (a difference of 2 per cent) while the range for the cella of the same temples is from *c.* 2.31 to 2.81 (a difference of about 22 per cent). In this case also, it is apparent that the planning did not proceed from the inside out, but rather from the outside in, and the consequence was that the spaces of the pteroma often differed substantially from front to side and in some cases from front to back. In the case of Athena Polias, its stylobate was 10 m longer than its cella, but only 5.6 m wider, and its cella ratio of 1:2.77 cannot have generated its column number ratio of 1:2.0.

The 6 x 12-columned series also provides a good indication of the impact which the imposition of ratios had on interaxials. Applying the column number ratio of 1:2 to the stylobate of Athena Polias resulted in its front and side interaxials being 20.8 cm different, which is a 5.4 per cent discrepancy. All six of the temples which were built after Athena Polias and which applied only one ratio to either their stylobate or krepis have interaxials which are the same within 2 per cent.

Corner contractions are sometimes said to relate to how much wider the architrave is than the triglyph, but if that were correct, the amount of contraction should ordinarily be the same on the fronts and sides. In the case of the Temple of Athena Polias, for example, the end interaxials of its sides are contracted 26.5 cm more than the interaxials of its fronts.

DESIGN OF THE PARTHENON

The Parthenon's column number ratio of 1:2.13 was applied to its krepis, which has the dimensions of 72.32 m by 33.69 m and a ratio of 1:2.15 (0.9 per cent discrepancy). In applying the column number ratio to the krepis, the Parthenon (Fig. 7) was typical of most Doric temples. It was most nearly comparable to the Temple of Hera Lacinia, Akragas, which had earlier applied a ratio of 1:2.25 to interrelate the measurements of as many of its design elements as possible (Fig. 6).[18]

The ratio 1:2.25 was probably chosen for the Parthenon because no other ratio had lent itself so well to achieving commensurability for a wider range of elements. This

Fig. 6. *Temple of Hera Lacinia, Akragas (Brogi; author)*

ratio had been applied with exactness for three major proportional relationships of the Temple of Hera Lacinia: (1) its stylobate width to length is 1:2.25; (2) its triglyph width to lower diameter is 1:2.25; and (3) its lower diameter to interaxial is 1:2.25. Hera Lucinia was probably designed in *c.* 460, and about thirteen years later Iktinos and Kallikrates applied the same ratio to a building with different column numbers and gave the same proportions to the same three sets of measurements and, in addition, to at least one other set of measurements.[19]

Although the architect of Hera Lacinia had been able to impose 2.25 on the front interaxial relative to its lower diameter, he had to settle for 2.3 for the side interaxials (with the side interaxials 5.4 cm narrower in mean width), and he also needed to contract his corner columns by an extra 8.5 cm in front and 7.9 cm on the sides. The Parthenon architects allowed its triglyph-to-lower-diameter ratio to differ very slightly in order to have nearly identical interaxials (regularly 4.2965 m and 4.2915 m; 5 mm difference; 0.1 per cent discrepancy).

To design the Parthenon, its architects had three basic requirements to fulfil: (1) to reuse a large number of the Older Parthenon's columns with a lower diameter of 1.905 m; (2) to maximize commensurability by using the 2.25 ratio; and (3) to use 8 x 17 columns rather than 6 x 13 as at Hera Lacinia. Since the column number ratio of Hera Lacinia was 1:2.17 and the column number ratio for the Parthenon is 1:2.13, the discrepancy of only 1.9 per cent enabled the architects to know in advance that the same series of 1:2.25 proportional relationships could probably be achieved.

Stuart and Revett discovered that the sides of the stylobate were 2.25 times the length of the fronts.[20] Penrose pointed out that the height of the order is 2.25 times the width of the stylobate, and Lloyd found that the interaxial was 2.25 times the lower diameter of the column.[21] In addition, the lower diameter of the column is 2.25 times the width of a triglyph (rather than 2 times the width of a triglyph as for the Hephaisteion and as recommended by Vitruvius). To achieve the highest possible level of commensurability was clearly an overriding goal.

Concealed within the krepis of the Parthenon is most of the krepis of the 6 x 16-columned Older Parthenon, which was under construction when the Persians burned the Acropolis in 480 B.C. The Athenians were able to salvage some column drums from the Older Parthenon, and they displayed the drums which were too damaged to be reused in the Acropolis' north wall. These damaged drums are on average within a millimetre of being the same size as those of the peristyle of the Parthenon, and they establish that the architects had to accept a given width for the lower diameter of their columns.[22]

With the lower diameter a given dimension, the architects necessarily had to divide the lower diameter by 2.25 to get the width of a commensurable triglyph, and they had to multiply the lower diameter by 2.25 to get a commensurable interaxial. Starting with a dimension they could not change, there was no other way to make the triglyph relate to the lower diameter and the lower diameter relate to the interaxial both as 1:2.25. When the actual diameter of 1.905 m is divided by 2.25, the result is 0.847 m, while the actual triglyph width is 0.841 m (6 mm smaller; 0.7 per cent discrepancy). When the actual diameter is multiplied by 2.25, the product is 4.286 m (which is 0.2 and 0.1 per cent different from the actual dimensions).[23]

When the plan of the Older Parthenon is superimposed on the plan of the Parthenon, it can be readily seen that these two buildings were designed using different systems of proportions (Fig. 7). None of the columns was placed in exactly the same location. Analyzing the archaeological evidence, B. H. Hill found that the interaxials of the Parthenon were made 4 to 6 cm narrower than the interaxials of the Older Parthenon.[24] Although this was only about 1 per cent narrower, the cumulative effect can be seen even on a small scale. The architects had enough room on the existing platform to retain the slightly wider interaxials of the Older Parthenon and also to add another interaxial to its end, but they felt so strongly that narrower interaxials were desirable that they had krepis blocks cut to correspond to the new plan and relocated every column. To be able to achieve a higher level of commensurability than had been achieved previously provides an explanation for why the architects revised the entire design and how they were able to persuade their clients to accept their expensive decision.[25]

Giving the Parthenon's stylobate the ratio of 1:2.25 made it fit easily within a slightly broader krepis with the ratio of 1:2.15, and these ratios allowed for steps of very nearly the same width. To have applied the 1:2.13 ratio of the column numbers to the krepis would have made the steps on the sides 32 cm broader than they are and 16 cm deeper than the steps on the fronts.

The krepis of the Older Parthenon was made of Kara stone (a hard limestone rather than marble), and since these steps were proportionately too short and too narrow as well as of being of a different material, the architects placed slightly taller blocks of marble in front of the Kara blocks. Rather than placing the Parthenon in the centre of the platform as the Older Parthenon had been placed, they encased the south side and let the north side extend onto bedrock.[26] With the south side a step wider, they moved the south columns outward by the width of a step (Fig. 7). They aligned the west end

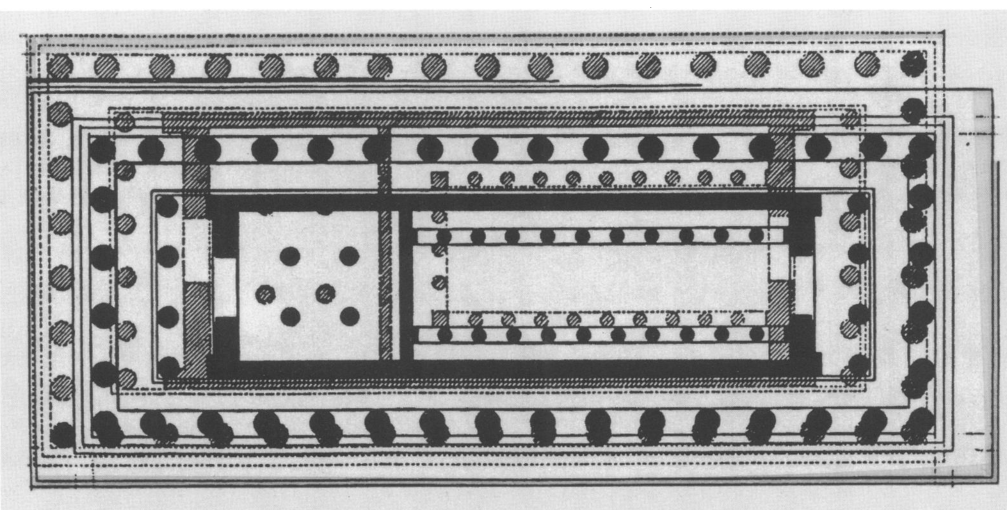

Fig. 7. *The plans of the Parthenon and older Parthenon in relation to one another (Hill,* American Journal of Archaeology, 16 *[1912])*

with the platform, and the extra column added to the sides was placed farther west than the columns of the Older Parthenon had been. The columns of the east nearly align with the position of the older columns, but were moved one step inward.

The joints of the euthynteria blocks do not align with the krepis blocks, as they do at the Hephaisteion, but the joints of the bottom and top steps nearly always align with column centres. Knowing where the columns later needed to go, the architects evidently marked the spacing for all interaxials on top of the euthynteria to guide in the cutting and placement of the krepis blocks.[27]

A new and fourth level of commensurability was achieved by dividing the 30.88 m width of the stylobate by 2.25 to determine the height of the order, producing a computed height of 13.724 m. The actual height of 13.728 m is 4 mm taller (0.03 per cent discrepancy). Ordinarily, the height would have been determined by multiplying three times the interaxial, but this would have produced a height of 12.89 m. The actual height of the order is nearly a metre higher than it would have been using the method which determined the height for the Hephaisteion and for most orders during the second half of the fifth century (Table 1, column 7). The order height to stylobate width at Hera Lacinia had been about 1:2.50 rather than 1:2.25.

Pliny the Elder (36.56) noted that some ancient temples were three times as wide as their column height (as opposed to order height). The Parthenon's stylobate is 2.96 times its order height (as opposed to column height) or very nearly 1:3 (1.3 per cent discrepancy). By contrast, three times the column height of the Hephaisteion bears no relation its stylobate (20 per cent discrepancy). The actual column height of the Parthenon is 10.433 m, making them by computation 32.00 Doric feet and almost exactly the same height as the columns of the earlier Temple of Zeus at Olympia (10.43 m or 31.99 Doric feet). If the architects had used the standard method, their columns would have been 10.296 m tall, which is three-quarters of the order height of 13.728 m (13.7 cm. shorter; 1.3 per cent discrepancy). Since they evidently preferred somewhat taller columns with an even number of Doric feet, the entablature had to be made 13.7 cm shorter to fit the 1:2.25 proportions of the front. The metopes had to be made shorter in height than in width and are consequently slightly rectangular rather than square.

Whole number of Doric feet had been widely used to plan the Temple of Zeus, Olympia, but do not seem to have been used for the Hephaisteion. The Parthenon's architects apparently used whole number of Doric feet in one other instance besides column height: the intended width of the side metopes was 4.00 Doric feet (1.305 m).[28] Judging by the correspondence between the sizes of the metopes computed for the Older Parthenon and by the spaces usually available for metopes of the Parthenon, it seems likely that at least some slabs intended for the Older Parthenon were reused regardless of when they first began to be sculpted.

The proportion for the height of the tympanum to its width is 1:9, which is the ratio Vitruvius recommended (3.5.12) and which he probably took from the treatise on the Parthenon by Iktinos, Kallikrates, and Karpion. The method Vitruvius describes implies that the heights of pediments were usually determined in relation to their width. The height of the Hephaisteion's pediment to its width was about 1:8.[29]

The overall proportions of the cella are 1:2.70, which is close enough to the 1:2.67 proportions of the Older Parthenon's column-number and krepis ratio that it was

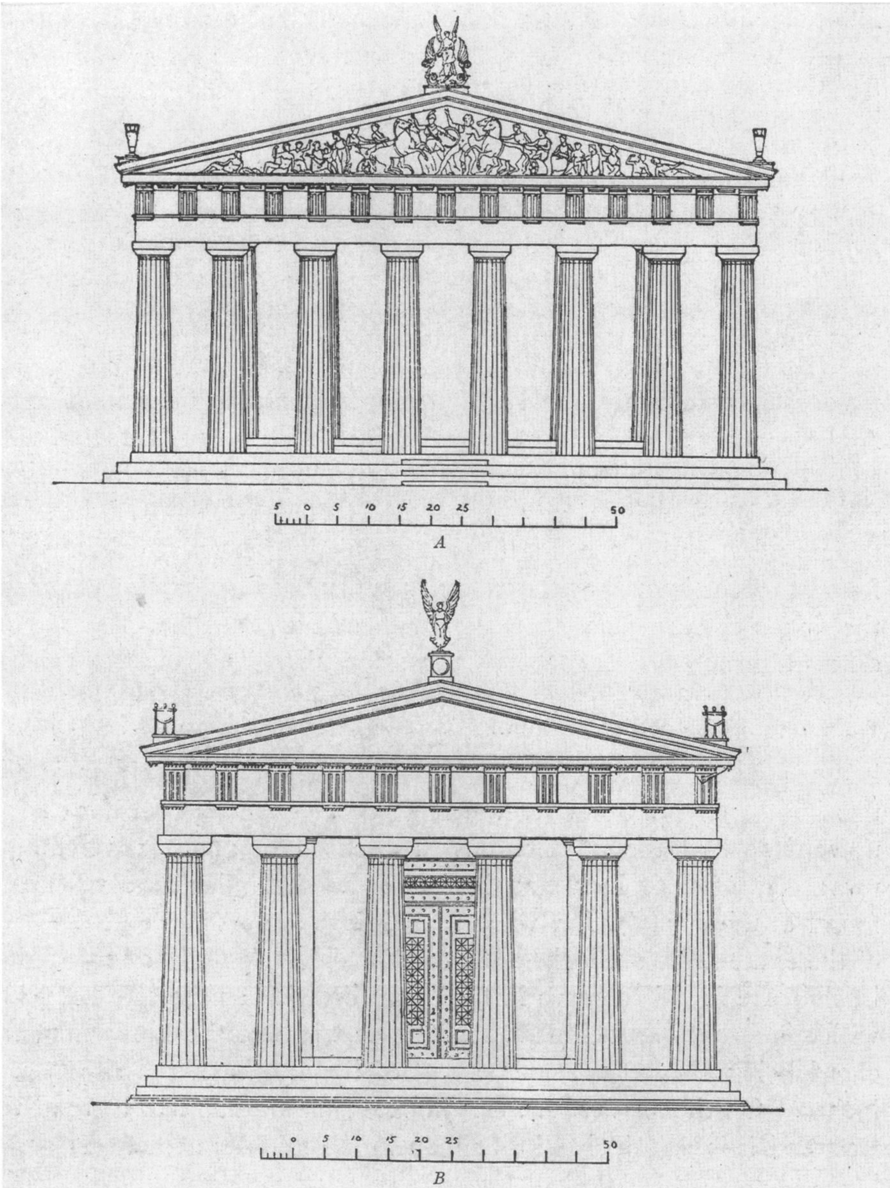

Fig. 8. *Fronts of the Parthenon and the Temple of Zeus, Olympia, drawn to the same scale by Sturgis (*History of Architecture 1, *[New York, 1906], fig.* 131*).*

possibly related.[30] Almost certainly, the length of the Parthenon's naos was made the length of the Older Parthenon's naos. Hill states that the Older Parthenon was laid out in Solonian feet, the standard of measure in use at the time, and if the length of the present naos is divided by the length of a Solonian foot (0.296 m) the naos is 100.6 Solonian feet long (0.6 per cent discrepancy). This is the most likely reason the naos of the Parthenon was referred to in fifth- and fourth-century inventories as the *hekatompedos*.[31] Whether any of the dimensions were considered to have a sacred significance or not, the cella was given an arbitrary length rather than aligning with the centres or edges of columns.[32]

Having settled on all of the principal features of the plan of the Parthenon, the architects were ready to lay out the plan at full scale on the euthynteria, which was made about 10 cm wider than the krepis on all sides.[33] They had basically determined the size of the stylobate when they fixed the size of the frieze. Using the actual triglyph and metope widths and multiplying by 15 triglyphs and 14 metopes, the width of the Parthenon's stylobate would be 30.913 m, and it was made 30.88 m or only 3.3 cm shorter (0.1 per cent discrepancy).[34]

If the architects had determined the width of the triglyph directly from the frieze rather than proportionally from the column diameters, the triglyphs would have been 0.849 m wide rather than 0.841 m (8 mm longer; 1.0 per cent discrepancy). The actual width (as opposed to the computed width) of the east architrave is 30.57 m, which is 31 cm shorter than the stylobate. The difference of 15.5 cm on each side can be almost entirely accounted for by an inward lean of about 6 cm and a projection beyond the column bases of an additional 6 cm.[35]

By giving the stylobate the preferred ratio of 1:2.25, the architects had to contract the corner columns substantially more than usual (to 85.7 and 86.0 per cent of the usual interaxial widths for fronts and sides respectively). The greater than usual contraction was caused by the compromises necessary to impose two ratios rather than one on the Parthenon: to make the column number ratio of 2.13 as similar as possible to the krepis ratio of 2.15 as well as to use the commensurable 2.25 ratio for the stylobate. Double contraction was a double fault needed to achieve greater commensurability. The Hephaisteion has about half as much contraction proportionally (93.4 and 93.5 per cent for fronts and sides), but its architect contented himself with applying his column number ratio to his krepis with great precision. He allowed his stylobate to have whatever ratio it turned out to be (1:2.32).[36]

The Parthenon's euthynteria was also where the curves of its krepis began, and it seems to have been given enough thickness to mark off the needed curves on its vertical sides. The minimum thickness of the euthynteria is 10.8 cm, and the maximum amount of the curve, 12.28 cm, is almost the same.[37]

Although the columns of the Parthenon's peristyle were made the same height, they were made from 16 to 20 cm thinner than the columns of the peristyle of the Temple of Zeus, Olympia, and they were placed nearly a metre closer together.[38] The differences in diameter make the Parthenon's columns 5.48 times as tall as wide, while the Zeus temple's columns were 4.64 to 4.72 times as tall as wide.[39] The columns of the Parthenon are thus nearly a full diameter taller and were conspicuously thinner in proportion, but narrower interaxials helped to make this less apparent (Fig. 8). As Pliny the Elder noted (36.56), the same columns placed closer together will appear thicker than they actually are.[40]

THE TEMPLE PLANNED FOR THE PLATFORM

The platform is substantially different in its size and proportions from the krepis of both the Older Parthenon and the Parthenon, and a number of scholars have argued that the platform was probably created for yet another temple. When the relatively small Older Parthenon was centred on the stone platform, much of the platform was not utilized. The platform was probably intended for a larger structure of poros rather than marble.[41] Working from the interaxial widths of early temples, Hill concluded that the platform was originally built for an immense 6 x 15-columned temple.[42] These column numbers had first been used for Apollo, Corinth, which is the only other temple with a cella plan similar to that of the Older Parthenon and the Parthenon. At about the time that the Parthenon's platform was created, Temple A (Hercules), Akragas, had recently been constructed with a krepis 27.30 m x 74.25 m, and the Parthenon's platform is 115 per cent of its width and 106 per cent of its length. As Hill suggested, there is a strong likelihood that the Parthenon's platform was built initially for a temple which would have been similar in plan and column numbers to Apollo, Corinth, and similar in scale and column numbers to Temple A, Akragas. Although Akragas may seem remote for Athens to be concerned with, it was also the site of the Temple of Hera Lacinia.

The column number ratio for the 6 x 16-columned Older Parthenon was 1:2.67, and its actual krepis ratio is 2.66 (26.190 m x 69.616 m) while the ratio for the dimensions of the much larger platform is 1:2.51, which is only 94 per cent the same. A 6 x 15-columned temple has the ratio of 1:2.50, which is within 0.41 per cent of being the same as the proportion of the platform. This is further evidence that the platform was, as Hill suspected, designed for a temple with 6 x 15 columns rather than 6 x 16 columns.

CONCLUSION

The types of proportional relationships discussed in this article have been shown to apply to multiple sets of measurements for single temples, to apply to the same sets of measurements for different temples, and to apply for some elements to the great majority of all temples for which comprehensive measurements are available. Buildings which differ greatly in form, size, date, and location have been shown to have used the same methods to achieve their principal proportions. A proportional relationship was definitely intended when the same sets of elements relate to one another in the same ways on more than one building. The correspondence between the proportions of the Temple of Hera Lacinia and the Parthenon provide a firm basis for determining how proportions were applied and reflect the amount of effort Greek architects were willing to expend to achieve commensurability.

In seeking to determine how Greek Doric temples were designed, Coulton wrote: 'The three criteria for assessing the probability that a proposed rule was in fact used will be: [1] that it can be simply expressed, [2] that it fits existing remains with a reasonable degree of accuracy, and [3] that it holds good for a number of buildings — preferably for a group of building from roughly the same place and period.'[43] These criteria will be used to evaluate the procedures which have been proposed in this article:

(1) One simple rule fits the great majority of all peripteral Doric temples for which comprehensive measurements exist: the ratio of the number of columns on the front to the number on the side was applied as the ratio for the width of a krepis to its length. No previously proposed rule applies to nearly as many temples. Another simple rule fits the great majority of Doric temples created from *c.* 450-*c.* 320 B.C.: the width of a triglyph was determined by dividing the krepis length by the number of columns times five. These procedures enabled a regular frieze to be planned so that the krepis blocks could be placed where they needed to be to align later with the columns and frieze.

(2) Coulton's independently established standard for accuracy of 2 per cent was adopted and was consistently applied to the data he assembled. No other standards have been used; no measurements have been substituted; and no other data has been preferred that might better support the argument. Additional data has been introduced only for architectural features which Coulton and Dinsmoor provided no data for.

(3) The results are an objective and readily confirmed demonstration that the column number ratio was applied to the krepis in 74 per cent of the temples for which comprehensive measurements are available (for 32 out of 43 temples) and that the triglyph corresponds to a predictable fraction of the krepis in 87 per cent of the temples constructed between *c.* 450 and *c.* 320 B.C. (for 13 out of 15 temples). Considering that these temples vary greatly in size and shape, such uniform results cannot be coincidental.

Using these results, it is possible to see how a temple could be fully planned before its foundation trenches were dug and to reconstruct a design sequence capable of generating actual measurements. By working out these basic principles of design in advance, it was possible to see how they needed to be adapted to design the Parthenon.

The sequence reconstructed for designing the great majority of Doric temples makes it possible to understand how commensurability could be achieved in a building as complex as the Parthenon and why problems such as contractions were unavoidable. The adoption of an entirely regular frieze required that corner columns be placed in line with the other column, and their required position is a vestige of the design process rather than the result of calculation. Differences in front and side intercolumniations were another vestige, but one which was minimized through the application of the column number ratio to the krepis rather than to the stylobate and by using more carefully selected column numbers. Even so, contractions were never greater than those required to impose two ratios on the plan of the Parthenon. Commensurability was considered to represent unparalleled harmony, but was achieved at some sacrifice of visual unity.

Vitruvius and Pliny were more familiar and concerned with Roman than Greek architecture, but both provide indications of how Greek architecture was designed. Vitruvius was codifying and reconciling procedures rather than recording or summarizing. Pliny was summarizing, but he too had access to Greek treatises which no longer survive. The number and types of proportional ratios given by both of these writers show plainly that there was nothing mysterious about how basic proportions were determined and used. Ratios were a convenient way to record and apply proportions which had proven to be structurally sound and visually effective. Proportions were achieved by relating one element to another usually through the use of whole numbers of modules or simple fractions, and although any element could be adopted for use as a module, triglyphs were the preferred module for Doric temples. Simple relationships formed the basis for the design of nearly all Doric temples, but their combination created designs of great complexity. The subtlety of the designs was continually increased through visual corrections to improve proportions and through optical refinements. It would be historically inaccurate to give the impression that the creation of Doric temples consisted of no more than following simple procedures, but without agreement on a few basic rules and the adoption of a few procedures, the potential of this building type could not have been so fully realized.

Many assumptions have prevented rather than facilitated ascertaining how Greek temples were designed. They were not created using complex geometric patterns. Substantially different design procedures were not adopted in different places. The design process did not change greatly for nearly two centuries despite great advances in Greek mathematics. Complex formulas and calculations were not required to work out proportions. Ordinarily, measurements could not be applied with as much precision as modules could be repeated.

When the design process is approached from the point of view of the architect and when what he had to know at each stage of construction is taken into consideration, it becomes possible to determine what the great majority of Greek Doric temples have in common. Largely correct data can provide largely correct results with reasonable allowances for inaccuracy, and greater precision will allow for better results when more comprehensive and comparable sets of measurements are available for all temples. Definitive results are likely to require excavation so that euthynteria can be examined for marks used to guide construction.

POSTSCRIPT

Mark Wilson-Jones provided me with a copy of his second article on Doric design, and we have discussed his article and my article in detail. As he noted, 'a forthcoming publication by Gene Waddell comes to parallel conclusions on the basis of Coulton's and supplementary data. There is a key difference with the present interpretation, however, in as much as Waddell believes the triglyph module to be derived from the krepidoma, rather than, as I see it, the other way around.'[44] The methods he proposed could have achieved the same results more easily, but there is evidence that Greek architects continued to use traditional methods of design.

The principal evidence is vestiges of an earlier design method. If the method had been entirely changed, it is likely that these vestiges would have disappeared. The difference in interaxial widths for the fronts and sides of early temples is a clear reflection of the application of the column number ratio to the krepis, and although the differences are usually small, they continue to be measurable. In some late temples, as at Segesta (424-416), they are considerable. The side interaxials of the temple at Segesta are 2.55 cm wider than its front interaxials. If its architect had used modules from the beginning of the design process, he could easily have made the interaxials the same on the fronts and sides, but, instead, he must have divided the number of interaxials for the fronts and sides into a predetermined size of the krepis.

Further evidence that this archaic design procedure persisted is the existence of a *hekatompedon* which is very nearly 100 Doric feet long, the Temple of Poseidon at Sounion (435 B.C?). It is 32.8 m long, and Wilson-Jones proposed that in this case a Doric foot of 0.328 m was used. He gives the size of a triglyph as 25 dactyls, which multiplied by 65 modules produces a length of 1,625 dactyls rather than 1,600 dactyls or 100 Doric feet.[45] To have used a triglyph 24 dactyls would have produced an overall length of 1,560 dactyls or 40 dactyls less than needed for 100 Doric feet. Since no whole number of dactyls comes as close to 100 Doric feet as the temple itself, it must be that a fraction of a dactyl was used to determine the size of the triglyph-module. The needed fraction could have been approximated by dividing 100 Doric feet by 65 modules and by making slight adjustments as necessary.

I believe I found persuasive evidence that the fronts of the Temple of Hera Lacinia and of the Parthenon were designed using 4:9 (1:2.25) for the ratios of their order heights to stylobate widths, and in both cases I included the geison as part of the order. Wilson-Jones proposed that the ratio of 1:2 was used for Hera Lacinia, and to achieve as accurate a fit as possible, he omitted the geison as part of the order while including it in six of his eight comparable examples.[46]

In searching for many different ratios between many different points, Wilson-Jones found many close matches. The ratios he proposes as having been intended for eight temples are in relation to five different sets of points: order height without geison to stylobate width, order height with geison to krepis width, order height together with krepis height to the axials of end columns, order height with geison to the axial of end columns, and column height to the axial of end columns. Between these various points, he proposes the following ratios: 1:2, 2:3, 3:4, 3:5, 4:9; and 5:9. His matches are consistently closer than mine, but mine fit more examples with a reasonable margin for error. He used more precise dimensions, but the dimensions I used were more comprehensive and more comparable to one another. He considered fewer examples within a narrower time frame and found that the same ratio is likely to have been applied to the same points on three buildings. We both agree that modules were used extensively to design Greek Doric temples, and he has established how important they were for elevations. My study focused more on plans.

ACKNOWLEDGMENTS

I am grateful to Andor Gomme for selecting two reviewers who were exacting, but fair. As a result of an anonymous reviewer's comments, I added the section comparing temples with 6 x 12 columns. Mark Wilson-Jones commented in detail, and his criticisms were consistently constructive.

APPENDIX

METRIC DIMENSIONS FOR DORIC TEMPLES

The first five dimensions are from Dinsmoor (n. 3; also used by Coulton, n. 4), and the last two are from Coulton (n. 4). Explanation: S = stylobate width by length; AX = regular interaxial (corner interaxials in parenthesis); LD = lower diameter of columns (corner columns in parenthesis); CH = column height; EH = entablature height; T = triglyph width; K = krepis width by length. When two measurements are given, they are for fronts and sides respectively unless otherwise noted. All dimensions are in metres.

1. Heraeum, Olympia: S 18.75 x 50.01; AX 3.56 (3.325), 3.26 (3.12); LD 1.20-1.28, 1.00-1.24; CH 5.22; EH ?; T ?; K *c.* 20.15 x 51.11.
2. Apollo, Syracuse: S 21.57 x 55.33; AX 3.772 (4.45 center), 3.331; LD 2.01, 1.84; CH 7.98; EH ?; T ?; K 24.46 x 58.32.
3. Olympieion, Syracuse: S *c.* 22.40 x *c.* 62.05; AX 4.08, 3.753; LD 1.84 side; CH approx. 8.00; EH ?; T ?; K ?25.40 x 65.05.
4. C, Selinous: S 23.937 x 63.720; AX 4.399, 3.860; LD *c.* 1.91, 1.81; CH 8.653; EH 4.48; T 0.87-1.08; K 26.357 x 71.150.
5. Athena, Assos: S 14.03 x 30.31; AX 2.61, 2.45; LD 0.915; CH 4.78; EH 2.02; T 0.56; K 14.85 x 30.86.
6. Apollo, Corinth: S *c.* 21.484 x *c.* 53.824; AX 4.028 (3.758), 3.744 (3.506); LD 1.744, 1.645; CH 7.24; EH ?; T 0.83; K ?
7. D, Selinous: S 23.626 x 55.679; AX 4.368, 4.491; KD 1.701; CH 8.31; EH 3.953; T 1.05; K 28.096 x 59.879.
8. Hera I (Basilica), Paestum: S24.51 x 54.27; AX 2.871, 3.102; LD *c.* 1.442; CH 6.445; EH ?; T ?; K 26.00 x 55.765.
9. FS, Selinous: S 24.370 x 61.88; AX 4.468, 4.604; LD 1.79; CH *c.* 9.11; EH 3.955; T 1.03; K 28.39 x 65.90.
10. Athena Polias (Peisistratid Temple), Athens: S 21.30 x 43.15; AX 4.042 (3.732), 3.834 (3.467); LD *c.* 1.63, *c.* 1.55; CH approx. 7.40; EH 3.999; T 0.822; K 21.85 x 43.95.
11. GT, Selinous: S 50.07 x *c.* 110.12; AX 6.53 east, 6.61 west front (6.29), 6.61 sides (6.57 west corners); LD *c.* 2.97 east and sides, *c.* 3.26 west; CH *c.* 14.69; EH *c.* 6.56; T 1.34; K 53.31 x 113.36.
12. Olympieion, Akragas: S *c.* 52.74 x *c.* 110.095; AX 8.042, 8.185 (7.985); LD 4.05; CH *c.* 17.265; EH *c.* 7.555; T 1.79; K c 56.30 x *c.* 113.45.
13. Athena (Ceres or Demeter), Paestum: S 14.541 x 32.880; AX 2.629, 2.625; LD 1.267; CH 6.127; EH *c.* 2.653; T 0.55; K 16.127 x 34.52.
14. Tavole Paladine, Metapontion: S 16.06 x 33.46; AX 2.956, 2.9255; LD *c.* 1.06; CH 5.135; EH ?; T ?; K *c.* 17.4 x *c.* 34.74.
15. A (Hercules), Akragas: S 25.284 x 67.040; AX 4.614 (4.501), 4.614; LD *c.* 2.085; CH *c.*10.07; EH 3.71; T 0.89; K 27.30 x 74.25.
16. Athena Pronaia, Delphi: S 13.25 x 27.464; AX 2.485 (2.345), 2.421 (2.285); LD 1.005, 0.975; CH 4.60; EH ?; T 0.511; K 14.25 x 28.45.
17. Poseidon I (old), Sunion: S *c.* 13.06 x *c.* 30.20; AX 2.449 (*c.* 2.306); LD 0.98 (*c.* 1.00); EH ?; T 0.52; K c 14.50 x c 31.80.
18. Aigina, Aphaia: S 13.770 x 28.815; AX 2.618 (2.40), 2.5605 (2.327); LD 0.989 (1.01); CH5.272; EH 1.966, 2.041; T 0.505; K 15.50 x 30.50.
19. Older Parthenon, Athens: S 23.533 x 66.940; AX 4.413 (4.075), 4.359 (4.0645); LD 1.903 (1.95); EH ?; T ?; K 26.190 x 69.616.
20. Athena, Syracuse: S *c.* 22.00 x *c.* 55.02; AX 4.15 (4.08 and 3.87), 4.65 (3.995 and 3.80); LD 1.92; CH 8.71; EH *c.* 3.90; T 0.84; K c 23.88 x c 56.90.

21. Nike, Himera: S 22.455 x 55.955; AX 4.175 (*c.* 4.11, *c.* 3.997), 4.198 (*c.* 4.084, 3.970); LD *c.* 1.875; EH ?; T 0.842; K 25.09 x 58.61.
22. ER (Hera), Selinous: S 25.324 x *c.* 67.735; AX 4.712 (4.405); LD 2.268; CH *c.* 10.15; EH 4.47; T 0.95; K 27.244 x 69.743.
23. Zeus, Olympia: S 27.68 x 64.12; AX 5.2265 (4.793), 5.221 (4.748); LD 2.25, 2.21; CH 10.43; EH 4.08, 4.155; T 1.06; K 30.20 x 66.64.
24. Hera II (Poseidon), Paestum: S 24.264 x 59.975; AX 4.471 (4.295), 4.503 (4.362, 4.223); LD *c.* 2.112, 2.036; CH 8.88; EH 3.788; T 0.90; K 26.06 x 61.70.
25. Hera (Juno) Lancinia, Akragas: S 16.910 x 38.100; AX 3.118, (3.033), 3.064 (2.985); LD *c.* 1.387, 1.332; CH 6.36; EH *c.* 2.90; T 0.615; K 19.74 x 40.895.
26. A, Selinous: S 16.129 x 40.303; AX 2.997 (2.929, 2.875), 2.9975 (2.903); LD *c.* 1.32; CH 6.235; EH 2.78; T 0.64; K 17.915 x 49.17.
27. Apollo, Bassai: S 14.478 x 38.244; AX 2.714 (2.506 north, 2.526 south), 2.673 (2.432); LD 1.161 north, 1.121 south and sides; CH 5.957; EH 1.948; T 0.536; K 15.84 x 39.57.
28. Hephaisteion (Thesion), Athens: S 13.708 x 31.769; AX 2.583 (2.413), 2.581 (2.413); LD 1.018 (1.038); CH 5.713; EH 2.020, 1.980; T 0.515; K 15.42 x 33.48.
29. Parthenon, Athens: S 30.880 x 69.503; AX 4.2965 (3.6815), 4.2915 (3.689); LD 1.905 (1.948); CH 10.433; EH 3.295; T 0.841; K 33.69 x 72.32.
30. Poseidon II (new), Sunion: S 13.470 x *c.* 31. 124; AX 2.522 (*c.* 2.374); LD 1.043 (*c.* 1.063); CH 6.024; EH 2.010, 1.990; T 0.51; K 15.2 x 32.8.
31. Ares, Athens: S *c.* 14.344 x *c.* 33.174; AX 2.690 (*c.* 2.53); LD *c.* 1.10 (*c.* 1.12); CH *c.* 6.275; EH *c.* 2.027, *c.* 1.967; T 0.554; 16.202 x 35.032.
32. Nemesis, Rhamnous: S *c.* 9.996 x 21.420; AX 1.904 (*c.* 1.730); LD 0.714 (*c.* 0.728); CH. *c.* 4.10; EH 1.394, 1.356; T 0.377; K 11.58 x 22.76.
33. Concord, Akragas: S 16.925 x 39.420; AX 3.195 (3.100, 3.005), 3.206 (3.111, 3.015); LD 1.452; CH 6.70; EH *c.* 2.96; T 0.64; K 19.62 x 41.99.
34. Segesta: S 23.120 x 58.035; AX 4.334 (4.230, 4.113), 4.3595 (4.225, 4.100), LD 1.955; CH 9.366; EH 3.585; T 0.85; K 26.26 x 61.17.
35. Hera, Argive Heraion: S *c.* 17.305 x *c.* 36.90; AX 3.266 (*c.* 3.041); LD 1.32 (*c.* 1.345); CH approx. 7.40; EH *c.* 2.48; T 0.65; K 20.09 x 39.60.
36. Asklepios, Epidauros: S *c.* 11.76 x *c.* 23.06; AX *c.* 2.27 (*c.* 1.99); LD 0.93; CH c 520; EH 1.520; T 0.441; K 13.20 x 24.45.
37. Apollo, Delphi: S *c.* 21.68 x *c.* 58.18; AX 4.138 (3.708), 4.083 (3.667); LD 1.806; CH *c.* 10.59; EH ?; T 0.82; K 23.82 x 60.32.
38. Athena Alea, Tegea: S 19.19 x 47.55; AX 3.613 (3.342), 3.585 (3.224); LD 1.55 (*c.* 1.575); CH 9.475; EH 2.421, 2.352; T 0.71; K 21.20 x 49.56.
39. Zeus, Nemea: S 20.09 x 42.555; AX 3.750 (3.453), 3.746 (3.452); LD 1.63 (*c.* 1.655); CH 10.368; EH 2.567, 2.484; T 0.730; K 21.957 x 44.221.
40. Zeus, Stratos: S 16.57 x 32.42; AX 3.17 (2.835); LD *c.* 1.31; CH *c.* 7.095; EH 2.071; T 0.625; K 18.32 x 34.12.
41. Metroön, Olympia: SS 10.62 x 20.67; AX 2.01 (1.82); LD 0.85; CH ?; EH 1.488; T 0.405; K 12.03 x 21.88.
42. Apollo II (peripteral), Delos: S 12.47 x *c.* 28.53; AX 2.2905; LD 0.945 (0.965); CH *c.* 5.20; EH 2.060; T 0.48; 13.72 x 29.78.
43. Athena Polias, Pergamon: S 12.27 x 21.77; AX 2.367 (2.175), 2.371 (2.175); LD 0.754; CH 5.260; EH 1.225; T 0.312; K 13.02 x 22.535.

NOTES

1 The principal conclusions in this article were presented in 'How the Parthenon Was Designed' at the annual meeting of the Society of Architectural Historians in St Louis, Missouri, in April 1996.

James Stuart and Nicholas Revett, *Antiquities of Athens*, 3 (London, 1762, 1787, and 1794), ch. 1, pl. 10. Stuart and Revett's drawings of the Hephaisteion show only two steps rather than the three which actually exist and are standard for the majority of Greek Doric temples. The lowest step was made of limestone instead of marble like the rest of the building, and they disregarded it as part of the foundation.

2 Nicolas Balanos, *Les Monuments de l'Acropole Relèvement et Conservation* (Paris, 1938), drawing no. 10.

Marina Yeroulanou noted that the alignment of every third joint of the first and third steps indicated advanced planning of some kind was done for the Parthenon before construction began ('Metopes and Architecture: the Hephaisteion and the Parthenon', *Annual of the British School at Athens*, 93 [1998], pp. 408 and 411).

The history of the Parthenon and information on its construction and restorations is summarized in M. Korres and Ch. Bouras, *Meleti Apokatastaseos tou Parthenonos* (Athens, 1983). Recent research on the Doric order is summarized in Mark Wilson-Jones, 'Doric Measure and Architectural Design 2: A Modular Reading of the Classical Temples', *American Journal of Archaeology*, 105 (2001), pp. 675-713.

3 William Bell Dinsmoor, *Architecture of Ancient Greece: an Account of Its Historic Development*, 3rd edn (London, 1950), appendix (pp. 337-40). All dates are from Dinsmoor unless otherwise noted. Although some dates are disputed, what was needed for this article was a largely correct sequence.

4 J. J. Coulton, 'Towards Understanding Doric Design: the Stylobate and Intercolumniations', *Annual of the British School in Athens*, 69 (1974), pp. 61-86 and tables 1-3.

The dimensions cited in this study are from Coulton's tables unless noted otherwise. Cella measurements are from D. S. Robertson, *A Handbook of Greek and Roman Architecture*, 2nd edn (Cambridge, 1964), pp. 324-30. Dimensions for the smaller elements of the Hephaisteion are from Herbert Koch, *Studien zum Theseustemple in Athens* (Berlin, 1955), pls 40-51.

5 These and a number of other conclusions could not have been reached without the observation by Coulton that 2 per cent was a reasonable tolerance to allow for the construction of Doric temples ('Towards Understanding Greek Temple Design: General Considerations', *Annual of the British School in Athens*, 70 [1975], p. 99).

In addition to errors of construction, allowing for a 2 per cent margin of error provides for a variety of other types of errors which have made measurements difficult to compare: modern measurements of temples may be somewhat inaccurate, may not be comparable when made by more than one person, and may have been converted to another system of measurement and rounded off; earthquakes and other disasters may have displaced blocks; and variations in local lengths for the Doric foot may be difficult or impossible to determine. There is often no way to be certain how much of an error has been introduced by any one of these factors, much less by more than one. Allowing an adequate allowance for all such possibilities is essential for meaningful patterns to emerge.

The 2 per cent margin of error used for this article means that a given measurement can be up to 2 per cent larger than a suspected ratio or up to 2 per cent smaller. This does not mean that the margin of error was actually 4 per cent; in no case does a computed amount differ by more than 2 per cent from an actual amount.

This margin of error is comparable to the margin which Coulton determined by dividing the extremes for the range of measurements of elements which would ordinarily be identical in size in the same building. Differences in centimetres (rather than millimetres) were not unusual, and in some cases he found ranges which were substantially more than 2 per cent ('General Considerations', pp. 95-97). When he compared the column number ratio to the krepis, Coulton allowed for an error of only 1 per cent greater than or less than the column number ratio ('Stylobate and Intercolumniations', table 2, col. 5), but this is less than the actual margin of error he found when considering how accurately buildings were ordinarily constructed (irrespective of additional types of errors).

The validity of using 2 per cent as the margin of error to compare the column number ratio and the krepis can be confirmed by considering what happens when the margin is increased: a margin of 1 per cent fits 17 temples; a margin of 2 per cent fits 32 temples (15 additional temples); a margin of 3 per cent fits 33 temples (only 1 additional temple); a margin of 4 per cent fits 34 temples (only 1 additional temple). In other words, doubling the margin from 2 to 4 per cent only adds 2 temples to the 32 which fit within the 2 per cent margin. A margin of 2 per cent is thus necessary to determine whether a relationship was intended between these ratios or not, and a margin of 1 per cent is inadequate to show what all of the buildings have in common.

Almost any conscientiously made complete set of measurements would suffice for comparison. As Coulton argued, it is better for comparison to use comprehensive measurements which are comparable than to use more recent or more precise measurements which are not comparable ('Stylobate and Intercolumniations', p. 67).

6 Dinsmoor attempted to determine Greek procedures through a close reading of Vitruvius, but he was initially misled by the Roman preference for using column diameters to determine intercolumniations ('How the Parthenon Was Planned: Modern Theory and Practice: Article II', *Architecture: the Professional Architectural Monthly*, 48 [July 1923], pp. 241-44). By 1950, when he produced the 3rd edition of his book, he included measurements for interaxials instead of intercolumniations.

7 For a literal English translation with an extensive commentary and numerous illustrations, see Vitruvius, *Ten Books on Architecture*, translated by Ingrid D. Rowland with commentary and illustrations by Thomas Noble Howe and with additional commentary by Rowland and by Michael J. Dewar (Cambridge, Mass., 1999). This edition is based on comprehensive studies of earlier translations and commentaries and on the advice of numerous specialists.

8 For Vitruvius' smaller Doric temple (Fig. 4), there would have been the equivalence of 7.5 triglyphs for each of the two side interaxials (3 triglyphs [including two half-triglyphs] and 3 metopes), producing a subtotal equivalent to 15 triglyphs. By making the centre equivalent to 10 triglyphs (4 triglyphs and 4 metopes), he brought the subtotal to 25. There was the equivalence of one triglyph to complete each end triglyph (with one half of a triglyph to either outside edge of each end column) and the equivalence of one more triglyph of empty frieze at each corner (half a triglyph at each corner), producing his total of 27 modules for the entire frieze and stylobate.

Although Vitruvius stated that he was describing a distyle temple (4.3.7), this was not quite the case. His temple would have had intercolumniations of 2.75 lower diameters rather than the 3 lower diameters he prescribed for distyle (3.3.4). Significantly, he gave the triglyph frieze precedence over using a whole number of column diameters to determine what his intercolumniations would be.

9 Koch, *Studien*: first measurement, p. 47; second, p. 47; and third, p. 49.

10 Vitruvius counted column numbers first across the front and afterwards along the side, counting the corner columns twice (3.2.5-6).

11 Thucydides (3.68) mentions a temple built for Hera at Plataea in *c.* 427 as being 100 feet in size. At least three surviving temples are within 2 per cent of being 100 Doric feet in length (nos 13, 30, and 40 in Table 2 and most notably Poseidon II, Sunion, which by computation is 100.61 Doric feet in length; 1.6 per cent discrepancy). The Hephaisteion is within 3.

I have used Dinsmoor's 0.326 m for the length for a Doric foot (Dinsmoor, *Architecture*, p. 195, n. 1). Coulton concluded that in 13 buildings, the foot used appeared to range from 0.325 to 0.332, but that in three-quarters of them (9 out of 13), the range was from 0.326 to 0.328 (a discrepancy of 0.6 per cent). Mark Wilson-Jones discovered that a metrological relief from Salamis has a Doric foot measuring from 0.327 to 0.3275 m in length or almost exactly in the middle of Coulton's estimated range ('Doric Measure and Architectural Design 1: the Evidence of the Relief from Salamas', *American Journal of Archaeology*, 104 [2000], p. 79).

No unit of measure used for Doric temples is known to have been smaller than a dactyl, which is $\frac{1}{16}$ of a Greek foot and about 2.0 cm. This means that measurements could ordinarily not be applied except to the nearest dactyl or applied more accurately than 1.0 cm (Coulton, 'General Considerations', pp. 92 and 93). However, many measurements were demonstrably executed with far greater precision than this, and they must have been marked off using dividers or equivalent tools for duplicating modules. The overall length of buildings which were apparently intended to be 100 or 200 feet long are usually somewhat longer, and the reason for this is likely to be that some additional length had to be added in order for an imprecisely determined module to be marked off an even number of times. The imprecise module could then be applied with precision, and every element based upon it would be exactly divisible by it.

For the purposes of facilitating comparison and computation, I have divided Doric feet into hundredths in the same way that surveyors divide the English foot into hundredths and for the same reasons. This is not meant to imply that Greek architects and craftsmen used the decimal system or that they used more precise units than dactyls. It is an artificial way of trying to determine if a whole number of Doric feet may have been intended for a building element.

There has long been disagreement about whether or not a standard foot existed in Athens or anywhere else in Ancient Greece. Every Greek stadium was 600 feet long, yet none measures the same and some vary substantially (Coulton, 'General Considerations', p. 87). By the mid-fifth century, the Doric foot seems to have been standardized throughout much of the Greek world to the measurements used for the Temple of Zeus, Olympia.

12 Koch, *Studien*, pl. 46. Fig. 31 has a setback of 15 cm.
13 Dinsmoor, *Architecture*, (p. 166) gives $\frac{3}{4}$ in. and $\frac{1}{4}$ in. (2.0 cm and 3.2 cm).
14 Dinsmoor gives the interaxial to order height as 1:2.99 and 1:2.98.

In most sixth-century temples the interaxial was not intended to be five triglyphs wide, but with essentially square metopes and with one full triglyph per intercolumniation, the result was often so close to 1:5 that this ratio could fairly readily have been discovered to be useful for planning purposes early on and even rediscovered.

For the variety of possible modules, cf. Vitruvius 1.2.4.

For the use of the 1.5 ratio for triglyphs to interaxials and 1:2 for triglyphs to lower diameters, see Table 1, columns 3 and 4. Altogether, six temples used both of these ratios at the same time, and in these cases the lower diameter to interaxial was necessarily 1:2.5 whether intended or not. At least 17 temples used the 1:5 ratio for planning purposes (Table 1, column 3).

15 Although Coulton found that the column number ratio seemed to have been applied to the krepis in as many as 17 out of 43 temples (39.5 per cent; Coulton, 'Stylobate and Intercolumniations', table 2), he concluded that interaxials were probably used to plan the stylobate of most Doric temples.

16 Douglas Arthur Clark concluded that the 2:3 ratio for triglyph to metope widths recommended by Vitruvius was the single most frequently recurring ratio for all elements of Greek temples except for some of the earliest in Italy. He did not indicate how the size of a triglyph was determined or utilized, but he noted the important fact that Vitruvius allowed the triglyph to determine what intercolumniations his Roman Doric temple would have. Clark also noted that the 2:3 ratio between triglyphs and metopes recommended by Vitruvius occurred as early as the oldest surviving stone entablature fragments which are preserved for the older Temple of Aphaia, Aigina ('Doric Proportions in Greek Monuments: 600-110 B.C.' [dissertation, University of Toronto, 1991], pp. 313, 317-18, 236, and 55).

17 Dieter Mertens, *Der Alte Heratempel in Paestum und die Archaische Baukunst in Unteritalien* (Mainz am Rhein, 1993), blilage 3. Mertens' measurements for individual stones are exemplary, but were not needed for this study. His overall measurements differ little from Dinsmoor's and Coulton's, and I have used theirs for more comparable results. For example, for the temple at Segesta, Mertens gives the stylobate width as 23.193 m while Dinsmoor gives it as 23.120 (differing by 7.3 cm, a discrepancy of 0.3 per cent).

18 For a discussion of early references to commensurability, see J. J. Pollitt, *Ancient View of Greek Art: Criticism, History, and Terminology* (New Haven, 1974), pp. 15-17 (especially Pl. *Phil.* 25D-E).

P. H. Schofield states that Vitruvius and Alberti show an implicit awareness of commensurability (the 'repetition of ratios'), but that Barca and Lloyd 'made explicit what before had been merely implied' (*Theory of Proportion in Architecture* [Cambridge, 1958], p. 102; cf. p. 94).

19 The relevant documentary evidence about Iktinos and Kallikrates is summarized and discussed in James R. McCredie, 'Architects of the Parthenon', in *Studies in Classical Art and Archaeology: a Tribute to Peter Heinrich von Blanckenhagen*, ed. by Gunther Kipcke and Mary B. Moore (Locust Valley, NJ, 1979), pp. 69-73. Kallikrates' qualifications are discussed by J. A. Bundgaard, *Parthenon and the Mycenaean City on the Heights* (Copenhagen, 1976), p. 48.

20 '... the third Step, on which the Columns of the Portico stand, measured 101 feet 1 $\frac{7}{10}$ inch English in front, and 227 feet 7 $\frac{1}{20}$ inch on each side, which are so nearly in the proportion of 100 to 225, that, had the greater measure been $\frac{1}{4}$ of an inch less, it would have been deficient of it' (Stuart and Revett, *Antiquities*), II, p. 8.

21 Francis Crammer Penrose, *An Investigation of the Principles of Athenian Architecture or the Results of a Survey Conducted Chiefly with Reference to the Optical Refinements Exhibited in the Construction of the Ancient Buildings at Athens*, new and enlarged edition (London, 1888), p. 118. W. Watkiss Lloyd, 'On the General Theory of Proportion in Architectural Design, and Its Exemplification in Detail in the Parthenon', in Penrose, *Investigations*, pp. 111-16; the analysis of the 4:9 ratio for column diameter to interaxial is on p. 113.

22 Ibid., p. 98.

23 In order to achieve this amount of commensurability, the architects had to settle for triglyphs which relate to the interaxial as 1:5.11 rather than 1:5.00, and although the discrepancy was only 2 per cent, the cumulative effect later required further adjustments. The slightly smaller triglyph which was adopted for commensurability (6 mm less than computed) is the reason why the ratio of the triglyph to krepis is almost 1:86 rather than 1:85 (17 columns x 5 triglyphs).

When the given diameter is divided by 2.25, the result is 99.3 per cent of the average triglyph width given by Coulton (0.841 m or 2.58 df). When the lower diameter is multiplied by 2.25, it is 99.7 per cent of the front interaxial and 99.9 per cent of the side interaxial.

24 B. H. Hill, 'The Older Parthenon', *American Journal of Archaeology*, 16 (1912).
25 Within a 2 per cent margin for error, three-quarters of the 13 temples designed between *c.* 495 and 440 used the 1:5 ratio for triglyph to interaxial, and it is likely that the architect of the Older Parthenon planned to do the same. No triglyphs are known to survive for the Older Parthenon, but if its stylobate length is divided by the number of triglyph-equivalents that its 16 columns would have had, the resulting width of a triglyph is within 2 per cent of being one-fifth of the known interaxial widths. Judging by this, the earlier architect intended to maintain the standard 1:1.5 ratio for triglyph to metope and had not intended for his triglyphs, lower diameters, and interaxials to be related as 1:2.25.
26 The masonry added to the south-east corner had long since settled and proved to be sound, and although the precaution of expanding to the north was wise, it proved unnecessary. The south-east corner is still slightly higher in elevation than the north-east corner, so little if any settling has taken place. The cracks in the east front must have been caused by earthquakes or by the 1687 explosion.
27 Yeroulanou ('Metopes and Architecture', p. 422) argues that a difference of 3.2 cm in the location of a joint of the top and bottom steps on the north side (for the second interaxial from the east end) indicates a change in plans caused by recalculation to determine the amount of contraction needed. However, as she indicates there is a difference of about 4.8 cm on the west front (for the fifth interaxial from the north end; her figures 1 and 3, lines 'F-G'). So large a discrepancy was highly unusual for the distances between the joints of krepis blocks that correspond to interaxials, but since the still larger discrepancy was clearly accidental and had nothing to do with corner contractions, it cannot be argued convincingly that the smaller error was significant. She acknowledged that no similar adjustments were made on either side at the west end of the temple, and she admits that it is doubtful whether or not a similar difference existed on the south side in the same relative position (p. 421). Since the amount of difference is too small to be clearly intentional and since there is no definite indication of a corresponding differences where they might be expected, this single measurement cannot be safely used to draw any conclusion about whether or not contractions were calculated.

Yeroulanou argues persuasively that the subject matter of metopes did not influence their dimensions. The sizes of metopes were thus determined by architectural, rather than sculptural, considerations.
28 Their intended width can be calculated by subtracting two triglyph widths from the side interaxials and then by dividing by two. Dividing 1.305 m by 0.326 m (Dinsmoor's Doric foot) equals 4.00. The intended width for the front metopes was 1.307 m. The metopes thus needed to be made 4.35–4.55 cm wider than 1.5 times the triglyph width.

The interaxials of the Older Parthenon are known to have been 4.413 m and 4.359 m, and having been designed after Aphaia, Aigina, it is could well have had a regular Doric frieze. If so, its triglyph would have been 0.870 m wide (computed by dividing the known krepis length of 69.616 m by 80 modules). This was significantly wider than the Parthenon's triglyph at 0.841 (2.9 cm wider; 3.4 per cent discrepancy). Multiplying 0.870 m time 1.5 produces a metope with the width of 1.305 m, which is 4.00 Doric feet (the same dimension intended for the metopes of the fronts of the Parthenon).
29 Koch, *Studien*, (pls 42 and 43) gives the height as 1.78 m and width as 14.49 m; $\frac{1}{8}$ of 14.49 is 1.81 (2 cm more; 1.7 per cent discrepancy).

The use of $\frac{1}{9}$ and $\frac{4}{9}$ appears to indicate a preference for ninths. An extraordinary characteristic of ninths is that each fraction from $\frac{1}{9}$ to $\frac{8}{9}$ divides out indefinitely with the same numeral that is divided by 9; 1 divided by 9 is 0.111... and 4 divided by 9 is 0.444..., and so forth.
30 D. S. Robertson gives separate dimensions for the overall length of all four sides of the cella: east, 21.72 m; west 22.34 m; north 59.02 m; south 59.83 m. (*Handbook*, p. 328). The ratio 1:2.70 is an approximation derived from the average for the two widths relative to the two lengths. There seems to be no good reason why the south wall should have been made 81 cm longer than the north wall or why the east wall should have been made 38 cm longer than the west wall, and the differences must be regarded as substantial, but inconsequential errors.
31 Philip A. Stadter, *Commentary on Plutarch's Pericles* (Chapel Hill, 1989), note on 13.7; other usage of this term are summarized, including its late fourth-century application to the entire Parthenon. Orlandos gives the length of the Parthenon's naos as 29.786 m. (A. Orlandos, *I architektoniki tou Parthenonos* [Athens, 1976-78], vol. 3, pl. 26 [with a minor transcription error corrected]). The number of Doric feet (as opposed to Solonian feet) for this measurement is 91.37.
32 Orlandos (*I architektoniki*; vol. C, pl. 26) shows that the alignment of the outside surfaces of the cella walls in front and back were not precise and that the cella columns do not come close to aligning with peristyle columns. The distances from the cella walls to the edge of the stylobate differ by as much as 58 cm (ibid., Atlas [vol. A], pl. 52).

33 Ibid., pl. 20.

34 Ibid., pl. 27. The range is from 1.237-1.333 m with the end metopes coming closest to an average width of 1.277 m.

The middle interaxial (fourth intercolumniation) measures 4.299 m, but the architrave block directly above it is 4.336 (3.7 cm more; 1 per cent discrepancy) while the next to last interaxial (sixth intercolumniation) is 4.300 m with a corresponding architrave of 4.150 m (15 cm more; 3 per cent discrepancy). Thus, four measurements which should have been identical have a range of 4.150-4.336 (18.6 cm; 4.3 per cent discrepancy). This is another example of measurements which should be the same, but which even in the Parthenon differ by twice the usual margin of error, and other examples have been given in notes 30 and 32. How carefully building blocks could be fitted together is a completely different matter from how precisely dimensions could be measured. For example, krepis blocks might be made various lengths except when their joints were expected to align with the centres of columns, yet regardless of their respective lengths would be joined with equal precision.

Although scale drawings were not needed to design and construct the Hephaisteion or the Parthenon, full-sized templates were undoubtedly used to ensure the uniformity of cornice profiles and the size of other elements such as triglyphs which were intended to be identical. Scale drawings as opposed to sketches or models would have been superfluous for laying out the plan, which could be done with sufficient precision only at full scale.

35 Penrose, Investigation, pls 7 and 8.

Most, if not all, columns seem originally to have been placed at the edge of the stylobate, but there has been much damage and restoration. Orlandos gives the amount of the stylobate projection as 0.6 cm for the east side at its north end and 5.8 cm for the south side at its east end (n. 31; vol. C, pl. 27). Dinsmoor, *Architecture*, (p. 166) gives the inward lean as $2\frac{3}{8}$in. (6.03 cm).

36 A number of attempts have been made to relate the 4:9 ratio to other parts of the Parthenon, to the Hephaisteion, and to other temples, but the proposed relationships have remained unconfirmed by parallels elsewhere. Frederick E. Winter suggested, for example, that '... the axial width of the two interior rooms [of the Parthenon's cella] combined is related to the axial length as 4:9, and the same is true of the outside dimensions of the colonnaded rectangle of the nave in the eastern rooms (counting the door-wall of the fourth side)' ('Tradition and Innovation in Doric Design III; the Work of Iktinos', *American Journal of Archaeology*, 84 [1980], p. 490).

Gruben wondered if it was a coincidence that the intercolumniation of the Hephaisteion related to the column height as 4:9 (1.6 per cent discrepancy), but since Doric temples were designed on the basis of interaxials rather than intercolumniations and since the column height was a fraction of the order height, this is unlikely. Similarly, he noted that the second step of the krepis had the proportion of 4:9, but no other example is known of a second step having been used to design a temple (Helmut Berve and Gottfried Gruben, *Greek Temples, Theatres, and Shrines* [New York, n.d.], p. 392).

Dieter Mertens searched for the use of the 4:9 ratio at Segesta and elsewhere in Italy and found that it appeared to have been used to determine the ratio of the column height to the width to the end interaxials of the fronts (*Der Temple von Segesta und die Dorische Tempelbaukunst des Grieschischen Westens in Klassischerzeit* [Manz am Rhein, 1984], beilage 24). By contrast, this ratio was used for order height to the full width of the stylobate for the Parthenon. In neither case is the ratio known to have been applied in the same way elsewhere.

Merten's drawings for Segesta reveal numerous important details such as the alignment of euthynteria blocks to column centres (as for the Hephaisteion).

37 Orlandos (*I architektoniki*), Atlas (vol. A), pl. 20.

38 The Parthenon's columns are 1.905 m wide and the columns of the Temple of Zeus are 2.25 m and 2.21 m. The Parthenon's interaxials are 4.2965 m and 4.2915 m, and the interaxials of the Temple of Zeus are 5.2265 and 5.221 m wide.

39 No earlier column heights come nearly as close to 32 Doric feet, and only two are at all close (A, Akragas, and ER, Selinous). So close a relationship between the columns of Zeus, Olympia, and the Parthenon is so singular that it is unlikely to be a coincidence.

40 The architects of the Parthenon appears to have borrowed both the height and proportions for their peristyle columns from Libon's pronaos columns. The 32 Doric-foot height of Libon's peristyle columns are twice the width of his interaxials, a design procedure which had been used earlier for seven temples, but none

of which is later than Hera Lacinia (Table 1, column 5). Since Libon used whole numbers of Doric feet in several other instances, the 32 Doric-foot height evidently originated as an integral dimension for the Temple of Zeus rather than the Parthenon (Dinsmoor, *Architecture*, p. 152). Sturgis' reconstruction (Fig. 8 herein) shows the columns of the Temple of Zeus too tall.

41 Dinsmoor (ibid., p. 150) states that the platform is solid stone. This made it possible to plan temples of such different size and proportions using the same foundation. Manolis Korres found through drill samples that the slope was cut into broad steps which could readily accommodate individual stones of up to two tons ('Architecture of the Parthenon', in Panayotis Tournikiotis, *Parthenon and Its Impact on Modern Times* [Athens, 1994], pp. 56 and 66, n. 3).

42 Hill, 'The Older Parthenon', pp. 556-57, 536. Hill rejected Dörpfeld's reconstruction of an 8 x 19 temple (which would have had a column number ratio of 1:2.38). He considered 8 x 20 to have been also less likely. The Olympieium in Athens (515-510 B.C.) was initially intended to have 8 x 21 Doric columns (1:2.63) and not 8 x 20 as is sometimes stated, but was corrected by Dinsmoor (*Architecture*, p. 91, n. 2).

There is no reason to believe that a larger foundation than necessary was created to provide a footpath. The construction fill to the south of the Parthenon provided adequately for this purpose, and that such a fill was originally intended is evident from the extreme irregularity of the courses of stone on the south side below the top three levels of the platform's cut stone (J. A. Bundgaard, *Excavations of the Athenian Acropolis, 1882-1890*, I [Copenhagen, 1974], figs 51 & 57).

43 Coulton, 'Stylobate and Intercolumniations', p. 61.

44 Wilson-Jones, 'Doric measure', p. 694.

45 Wilson-Jones, 'Doric measure', p. 704.

46 Wilson-Jones, 'Doric measure', p. 685.