rules is very probably correct. The capitals of the temple of Athena Alea were probably made on the basis of one design,[7] and the variation in their proportions could be produced either purposely or by inaccurate copying of this design.[8] The masons at Tegea were extremely skilled, as is shown for example by the elaborately decorated mouldings inside the cella,[9] and, therefore, it is clear that the capitals did not have to be millimetre exact copies of each other. The range of both abacus and echinus height differences is less than a centimetre: the smallest abacus height value, 0.243 m, is only 3% smaller than the greatest value of 0.251 m; the corresponding echinus heights are 0.158 and 0.167 m, the former being 6% smaller than the latter. The range of the proportion $\frac{\text{echinus height}}{\text{abacus height}}$ is 0.636–0.687, and the proportional difference, 8%, is now greater than the individual differences, mainly due to block 133 which has a low abacus and a high echinus. Here we have a case where the capital measurements can be taken to three significant figures, but variation in the dimensions makes the *second* decimal place of the proportion range (0.636–0.687) non-significant. Generally, the third decimals in the capital proportions at Tegea should simply be ignored. The normal procedure of dating the capitals on the basis of proportional analysis requires the use of at least two and often three significant figures to elucidate the differences between the build-

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[7] Usually a full scale specimen, a *paradeigma*, was made and the capitals then copied from this; Coulton 1977, 55–57, 104–108.

[8] In the temple of Apollo at Bassai the differences in the peristyle capital proportions were obviously intentional: “The several permutations of heights and diameters suggest a conscious and sequential alteration of elements as the capitals pass in transition from one size to the next.” Cooper 1996, 233. One possible source for the proportional variation in the Tegea data could be errors in the new measurements: great care was taken to reduce these to the minimum, by the use of appropriate tools and by rechecking the measurements.

In Greek architecture, generally, some variation in dimensions seems, in many cases, to have been preferred over ‘mathematical’ exactness. The Parthenon on the Athenian Acropolis provides classic examples, such as the abacus width of the normal column capitals which varies by almost 6 cm (1.997–2.055 m; Balanos 1938, 38), and the variation in the length of the five architrave blocks on top of the normal column bays of the east front of the Parthenon: they should all be of equal length, but the difference between the shortest and longest block is 0.18 m. The bays vary only by 0.01 m, thus causing the architrave joints to be significantly off the alignment of the columns. (Balanos 1938, dépliant no. 10). J. A. Bundgaard suggests that the differences in block lengths are explained by the reluctance of the masons to cut away more than was absolutely necessary of the blocks coming from the quarry: the four largest blocks were probably used to the full and only the shortest block cut down (Bundgaard 1957, 140f.). Quite often these examples have been overlooked even in modern studies, and the precision of the workmanship—e.g. the jointing of blocks is very accurate—is taken to apply to all of the building; on variation and accuracy, see Coulton 1975, 89–98. The refinements—the slight intentional deviations from the vertical, horizontal and rectilinear—used in Greek architecture are one aspect which suggests that variation was sought after by the architect rather than just tolerated; on refinements, see p. 41, and e.g. Coulton 1977, 108–113; Korres 1993b; Lawrence—Tomlinson 1996, 125–128.

[9] Dugas *et al.* 1924, pls. 64–65, 74–75, and 77–80.

ings.[10] Thus, the measurements taken of the Tegea capitals also support Coulton's second conclusion: the use of architectural proportions to date buildings must be reconsidered.[11]

The abaci of the three complete capitals that it was possible to measure—blocks 501, 539, and 562—show no certain sign of having been prepared for horizontal curvature: the abacus height measurements vary by 1–2 mm, but the top surfaces are flat: no indications of angles to adjust the surfaces to the broken curve formed by the architrave blocks were detected.[12] But the adjustment of capital top surfaces cannot be ruled out: block 562 is from the corner, and if it was adapted to horizontal curvature, it would have been necessary to fit it to the curving entablature of both the short and long sides of the temple.[13] The original position of blocks 501 and 539 is unknown: there is a clear cluster of six capitals to the west of the temple, and, if they are from the back short side of the temple, all capitals from that part of the building are preserved. The relative lack of capitals to the north and south of the temple foundations could be explained by the narrowness of the excavated trenches;[14] it is quite likely that there are more capitals lying in the unexcavated parts of the sanctuary. Another possibility is that some of the capitals presently in the western part have been moved there from the flanks of the temple to be reused in some later structure. Blocks 501 and 539 could both be from the middle of the colonnades where the required adaptation is less than that closer to the corners of the temple—there is a parallel to the measured height differences of 1–2 mm at Tegea in the Parthenon colonnade.[15]

One partially preserved capital, block 516, was probably adjusted for horizontal curvature: on the east side of the capital the total height of the block is 0.592 m and the abacus height 0.250 m; on the south side the same dimensions are 0.595 and 0.246 m. Thus, even though the abacus height is slightly lower on the

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[10] See e.g. Michaud 1977, 37–39 and app. III; and more recently, Miles 1989, 160–162. Coulton has avoided the danger of inaccurate data by the use of statistics over a large number capitals, so that even if there are errors, they are less likely to lead to false conclusions. E.g. when the single error I came across in checking Coulton's figures is corrected, the proportion AbW : $Diam_{LA}$ for the Metroon at Olympia is actually consistent the with rest of the proportions (table 17: the figure for the proportion is 1.05, not 0.93684 as given; for the values used in the calculation, see App. D, Table D1 and Adler *et al.* 1982, 37). To Coulton's credit it can also be said that even though the quotients in the tables are given to five decimal places, he has not given any weight to the insignificant digits; Coulton 1979, 82–103.

[11] The difficulty of chronological schematisation of capital proportions has also been observed by F. A. Cooper in connection with the Bassai temple; Cooper 1996, 233.

[12] See Fig. 18 on p. 47 for a reconstruction of the Tegea west peristyle order with exaggerated distortions and adjusted abaci.

[13] Balanos' illustrations of the Parthenon colonnade show no adjustment of the corner abaci; Balanos 1938, dépliants 10–11.

[14] See the plan in Fig. 11 on p. 32.

[15] In the centre of the colonnades Balanos recorded the same abacus height variation, 1–2 mm, as in the new measurements at Tegea. The maximum height difference measured by Balanos in a single capital is 7 mm; Balanos 1938, dépliants 2, 10, 11.

south face, the total height there is greater than on the east side of the block. Unfortunately, the block is only half preserved and lying upside down, so it is not possible to reach any definite conclusions. For these we must study the evidence of horizontal curvature in the foundations and the entablature.

IV. Horizontal curvature

Among modern scholars there is no general agreement as to the purpose of horizontal curvature in Greek architecture. Curvature of the stylobate is explained by Vitruvius as an optical correction: if it was level, it would appear to be hollow in the centre.[1] Even though modern empirical observation does not seem to support the optical illusion theory,[2] some scholars accept Vitruvius' statement on the purpose of refinements as the original intention of the Greek architects while others reject this and regard the curving lines as intentional avoidance of straight lines. The latter view is best expressed by J. J. Coulton: "they [the refinements] were intended to save a temple from a mechanical, lifeless appearance, and to create a slight and desirable tension between what the eye saw and what the mind recognised as the underlying form."[3] Both of these views can be argued for,[4] and for the stylobate curvature there is also the practical reason of shedding rain water.

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1 Vitr. 3.4.5.

2 See e.g. Goodyear 1912, and Rankin 1986.

3 Coulton 1977, 109. The former view is held by e.g. Dinsmoor 1950 (1985), 165, and the latter by e.g. Goodyear 1912, 102. Rankin goes further in the rejection of the optical correction theory and regards the refinements as "visual reinforcement of the temple's stability, its load-bearing and its scale." Rankin 1986, 40.

4 Coulton gives the literary and archaeological support for the views: Coulton 1977, 109–110 and 175–176 ns. 24–31.

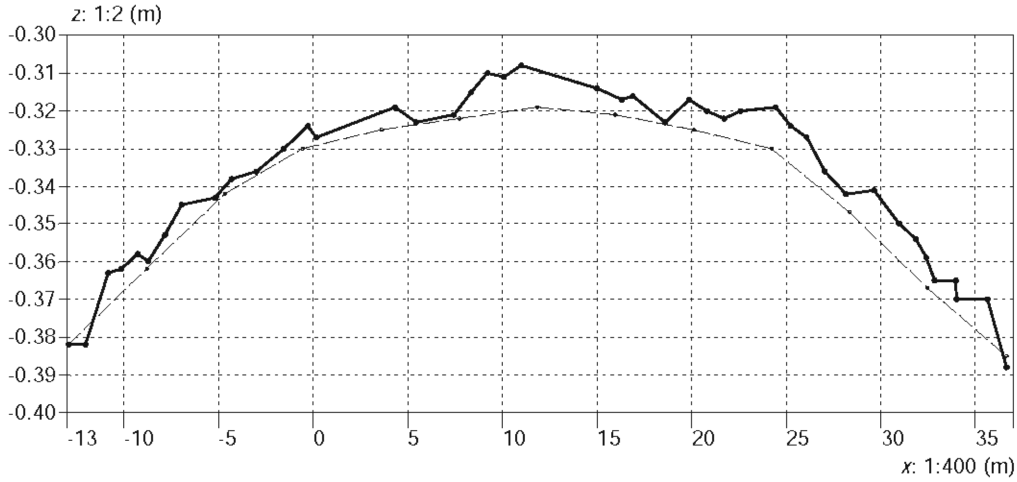

Fig. 15. Horizontal curvature of the foundations on the south long side. Values on the *x* and *z* axes are the *x* and *z* co-ordinates of the general co-ordinate system of the sanctuary. Solid line: new measurements; dotted line: Clemmensen's measurements. Scale on *x* axis 1:400 and on *z* axis 1:2.

1. Foundations

The curvature of the foundations of the temple of Athena Alea at Tegea had been measured by M. Clemmensen and Ch. Dugas,[5] and this was rechecked in 1998 with a theodolite and an electronic distance meter. To minimise the effect of the unevenness of the top surfaces of the conglomerate foundation blocks a piece of hardboard of 600 × 500 × 4 mm was used; the measurements were taken at the edge of the board as close as possible to the edge of the foundations. Only the south long and west short side of the temple could be measured, as foundation blocks on the north flank are largely missing, and the views to the edge of the east front from the current fixed station points of the theodolite are mostly blocked by column drums on the foundations. The measurements were taken from the origin of the general co-ordinate system of the sanctuary.[6]

Figure 15 shows a plot of the new measurements compared with Clemmensen's measurements on the south side from west to east. The measurements do not exactly coincide,[7] and in general the curve in Clemmensen's measurements is slightly less pronounced than in the new ones. The foundation curve is quite symmetrical: the east end is 6 mm lower than the west, and the mid part of the foundations is 80 mm higher than the east corner. The angle between the start of

5 Dugas *et al.* 1924, fig. 1.

6 The co-ordinates of the origin station point are (0, 0, -0.366). The thickness of the hardboard has been subtracted from the measurement data used in the following discussion.

7 The general error margin of the EDM is 1 cm, but the error in the *z* co-ordinates for nearly horizontal sightings is much less: even if the prism is not held completely motionless in the horizontal plane, the height of the prism remains constant due to the supporting rod.

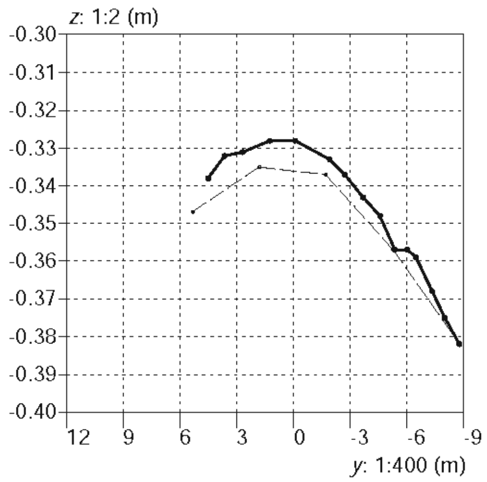

Fig. 16. Horizontal curvature of the foundations on the west short side. The blocks of the north-east corner foundations are partially missing. Values on the *y* and *z* axes are the *y* and *z* co-ordinates of the general co-ordinate system of the sanctuary. Solid line: new measurements; dotted line: Clemmensen's measurements. Scale on *y* axis 1:400 and on *z* axis 1:2.

the curve and the horizontal at the south-east corner of the foundations is ca. 0.5°.[8]

Figure 16 shows the measurements taken along the west short side of the temple: due to missing blocks on the north side (on the left in the figure) not all the measurements could be taken. The maximum height difference is 54 mm and the angle at the south-east corner is ca. 0.6°.[9]

The foundation curvature according to the new measurements is slightly more pronounced than that according to Clemmensen's. The solid lines in Figures 15 and 16 are not as smooth as Clemmensen's broken curves, but this is mainly due to the measurement of more data points in the new study. The horizontal curvature of the foundations is systematic and clearly intentional, and, as previously argued, the curvature at stylobate level was very probably approximately the same as at foundation level.[10]

[8] The height difference between the corner and at 2.07 m to the east of the corner is 0.019 m: the angle a is solved from tan a = 0.019 / 2.07.

[9] The height difference between the corner and at 2.25 m to the north of the corner is 0.023 m: the angle a is again solved from tan a = 0.023 / 2.25.

[10] See pp. 25–26, esp. n. 46 on p. 25.

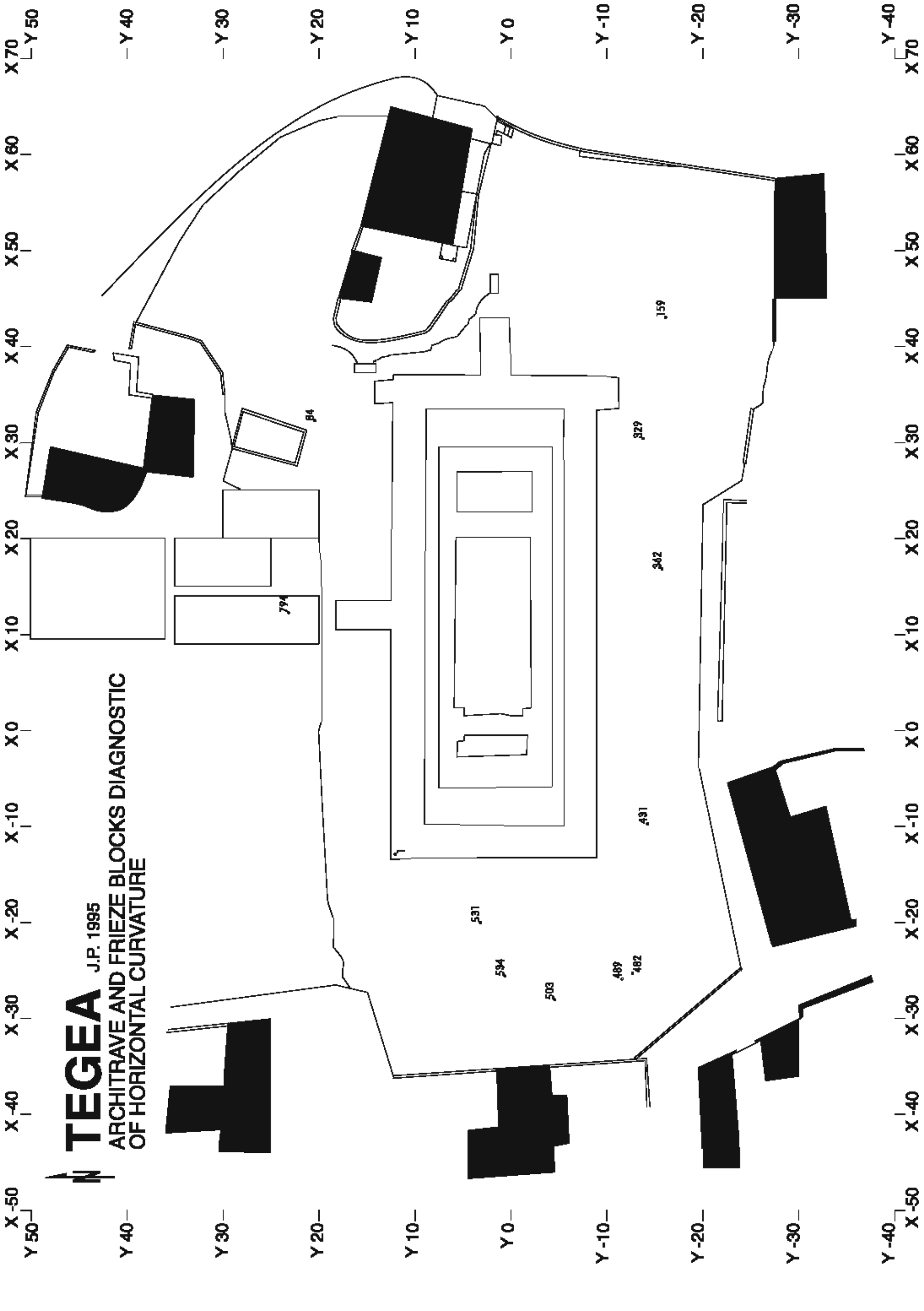

Fig. 17. Plan of architrave and frieze blocks diagnostic of horizontal curvature with block numbers.

2. Entablature

The existence of horizontal curvature in the entablature is crucial in determining the height of the columns: if the columns were standing on a curving stylobate and the architrave on top of the columns was straight, then the range of possible column heights would be quite large. For a curving entablature, however, even if the angles cannot be exactly determined, there is less height variation.

Of the 25 architrave blocks or fragments within the sanctuary, six have preserved at least one corner where it is possible to measure the angle in order to check whether it was adjusted for horizontal curvature. The statistics are similar for the frieze blocks and fragments: of the 28 blocks six have an adequately preserved corner for the purposes of this study. These blocks are listed in Appendix C and their locations in the sanctuary are shown in Figure 17.

The angle measurements of the corners were taken using a large metal square: if the angle was not 90°, one arm of the square was held tightly against one surface of the block and the distance between the other surface and the square was measured.[11] If the square fitted tightly to the edge of the block, then the angle was determined to be less than 90°; angles greater than 90° caused space to be left between the square and the stone at the corner of the block. For acute angles the distance between the square and the block surface was measured as far away as possible from the corner of the block (0.715–0.82 m). In measurements of obtuse angles the tip of the shorter arm of the square touches the block surface at 0.47 m[12] and the distance at the corner was measured by use of a long steel ruler set tightly against the block surface. Calculation of the angle from these measurements is more reliable than a direct angle measurement taken at the corner with a goniometre because in this way the measurements can be taken over longer distances. All the measurements were taken by two persons.

All six of the measurable architrave blocks and three of the six frieze blocks were discovered to be adjusted to horizontal curvature: the range of angles is 89.7–90.8°.[13] The most likely explanation for blocks having a corner cut into an angle differing from 90° is that the vertical joints of the blocks were kept at least almost vertical, but the bottom and top surfaces of the blocks were cut to form the broken curve of the entablature. Frieze block 431 has a corner cut into a

[11] See photographs on p. C2 of App. C.
[12] The length of the shorter arm is 0.500 m and the width 0.030 m (0.500 m – 0.030 m = 0.470 m).
[13] See Appendix C. Even though it may appear that the angle measurements are calculated to three significant figures from data with one significant figure, this is not the case: the calculated angle is always a small acute angle (0.1–0.8°) which is then subtracted from or added to a right angle. Clemmensen actually noticed the acute angle of block 159, an architrave fragment, and recorded it in his drawing of Dugas *et al.* 1924, pl. 39A, but this observation is not discussed in the publication. Block 482, an inner architrave block, has a corner cut into a right angle, but it is most probably matching with block 503, an exterior architrave block, which has the bottom surface adjusted to horizontal curvature.

right angle: it is from the corner of the building, and as the architrave block 1, the side of the block facing the façade and the top surface form a right angle (see Appendix C). The two other frieze blocks with 90° corners, 362 and 489, were possibly from the middle of the entablature where no angle adjustment is necessarily required.[14] Anyhow, the joint between two frieze blocks was not visible: it was covered by the slight projection of the triglyph over the metope.[15]

On the basis of two architrave blocks (503 and 531)[16], each with two preserved corners, it is possible to reconstruct the execution of the curvature of the architrave at Tegea. Block 503 has both corners with right angles, but there is a slight tilt in the bottom surface. The vertical side of block 531 forms an obtuse angle with the bottom surface, and an acute angle with the top. Figure 18 presents a reconstruction of the western colonnade with exaggerated horizontal curvature, and in the figure both of these blocks are placed in their original positions: block 503 is the left end of the architrave block above the centre bay of the west façade of the temple, and block 531 is the right end of the left corner architrave.[17] As block 503 demonstrates, besides cutting the top of the abacus to accommodate the broken curve of the entablature (as in the Parthenon[18]), it is also possible to slightly adjust the bottom surface of the architrave.

The three top column drums in Figure 18 are placed in their respective places in the figure on the basis of their present location west of the temple foundations (see Fig. 8 on p. 21) and the measured height differences.

The adjustments of the bottom and top drums and the architrave blocks suggest that the horizontal curvature of the foundations, krepidoma and entablature was approximately equal; it is very probable, therefore, that all the peristyle columns were of equal height.

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[14] For comparison, see Fig. 18.

[15] Dugas *et al.* 1924, pls. 41–43.

[16] The measurements of these crucial blocks were rechecked in the 1996 season.

[17] The blocks are restored to their positions on the basis of the adjustments and their present positions in the sanctuary.

[18] Cf. e.g. Lawrence—Tomlinson 1996, fig. 109.

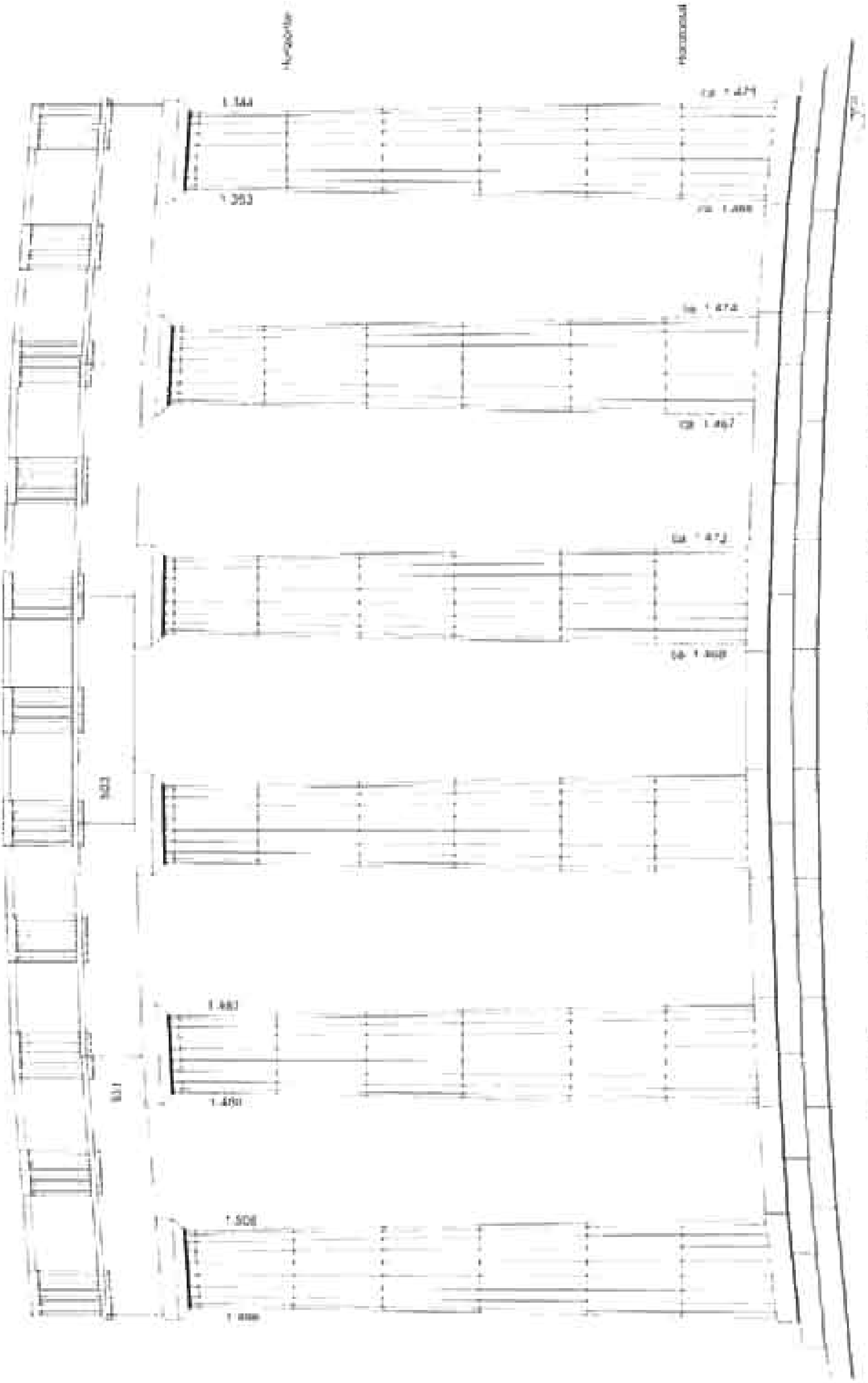

Fig. 18 Exaggerated horizontal curvature of the west façade of the temple of Athena Alea.

V. Column Height and Shaft Profile

1. The Dugas & Clemmensen Reconstruction of the Column Height

As we have seen, the height of the drums in the first two levels (*A* and *B*) is almost constant, but from the third to sixth levels (from *C* to *F*) there is considerable variation.[1] Dugas describes their method for matching the column drums as follows:

> "Cette reconstruction graphique se fait de la façon suivante: soit un tambour inférieur A, de hauteur *a*, que l'on reconnait à son plus grande diamètre à la face inférieure; on constate que, à la hauteur *a* de sa face supérieure, le diamètre n'est plus que $a - x$. Parmi les tambours, l'on cherche celui dont le diamètre inférieur est égal à $a - x$, et on place ce tambour, que nous appellerons B et qui est haut de *b*, au-dessus du tambour A. On peut ainsi dessiner la colonne jusqu'à une hauteur de $a + b$. Le diamètre supérieur du tambour B étant égal à $a - x - y$, on cherche ensuite le tambour C dont le diamètre inférieur aura cette dimension; on dessinera ainsi la colonne jusqu'à la hauteur $a + b + c$, et ainsi de suite jusqu'au tambour ayant le plus petit diamètre, tambour dont le diamètre supérieur est égal au diamètre infériuer du chapiteau."[2]

Dugas' and Clemmensen's algorithm for reconstructing the column height is per-

1 See p. 22.

2 Dugas *et al.* 1924, 19 n. 2.

fectly reasonable, but Dugas' certainty of the exactness of their result is quite surprising,[3] especially in the light of the doubts expressed by Clemmensen only slightly later.

Clemmensen's doubts are based on a comparison of measurements of the temples of Zeus at Nemea and Athena Alea at Tegea. He suggests that different foot units were used at Nemea and at Tegea and presents a table of 14 dimensions: the dimensions expressed in round numbers of 'Nemea feet' are equal to 'Tegea feet' in eight of the cases. The ninth possible match is the height of the peristyle columns. The height at Tegea does not seem to fit the pattern and it can only be expressed by using fractions of the 'Tegea foot'. Clemmensen gives two possible explanations: Firstly, there could be an error in the Tegea reconstruction. Instead of 31¾ feet the height could have been 33 feet as at Nemea. The missing 1¼ feet correspond to the height of one of the cella wall blocks. The height of the column would in this case be 9.847 m instead of the originally reconstructed 9.474 m. Secondly, he suggests that the column at Tegea could have been designed to be lower than at Nemea and that perhaps some other height, such as the height of the column and architrave together, was designed to be a round number of feet.[4]

Clemmensen's argument is not very convincing,[5] but it is significant that he himself, in the paper, doubts the published reconstruction of the temple. The contradiction between this attitude and the emphasis of mathematical exactness in the 1924 publication is striking, but Clemmensen gives no explanation for this.[6]

2. Determining the Height of the Column

The heights of individual column drums are measured along the outer edge; this means that when one adds together the height measurements of the drums, the result is actually the length of the polygonal line which is approximately the same as the length of the column shaft face with entasis (Fig. 19). If we take a hypothetical

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3 See p. 1 n. 2 for Dugas' quote.

4 Clemmensen 1925, 11–12.

5 In the worst case the proposed matching dimension expressed in feet and meters at Nemea is almost a foot unit off the mark (length of the euthynteria), at Tegea there are three dimensions for which Clemmensen did not even try to find a match, and the selection of dimensions presented in the table on p. 11 is far from being exhaustive. Also, the presented foot units for Tegea and Nemea are far from being certain: on the foot unit at Tegea and on the difficulty of determining foot units used, see Bankel 1984, 413–430; Hill's suggestion for the foot unit at Nemea 0.32565 m (Hill 1966, 9 n. 23) is significantly different from Clemmensen's 0.312 m (Clemmensen 1925, 11). On foot units and proportions, see also Coulton 1975, 85–89.

6 There are several possible reasons—perhaps Clemmensen did not express his lack of conviction when working with Dugas, or this issue was left out of the publication by Dugas, or perhaps Clemmensen only later came to have second thoughts—but without further evidence, no certain explanations can be given.

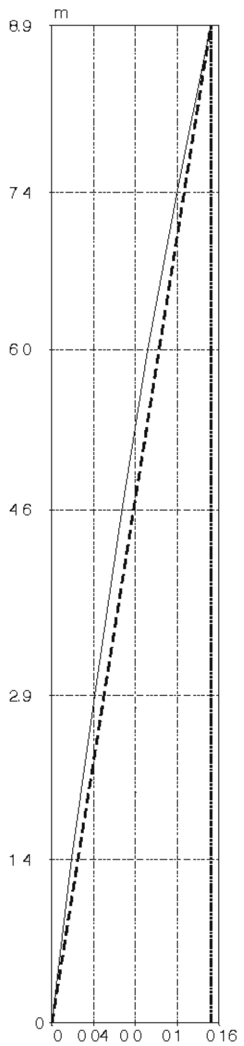

Fig. 19. Polygonal, hypotenuse, and true height of a column shaft.
——— polygonal height
------ hypotenuse
-·-·-·- true height
Differences on *x* axis exaggerated.

example of a column shaft consisting of blocks 51, 529, 9, 415, 401, and 542, the length of the polygonal line and the hypotenuse is 8.973 m, whereas the true height is 8.972 m.[7] As we can see from this example, the polygonal height is only a millimetre taller than the true height; this difference is insignificant because even in a single drum the error margin of the height measurements is greater than a millimetre. Therefore, the polygonal height, rather than the true height, is used to determine the height of the column shaft. Likewise, when the height of a single

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[7] Polygonal line = 1.474 + 1.473 + 1.668 + 1.447 + 1.411 + 1.500 = 8.973 m (for the heights, see App. A); true H = $\sqrt{a} + \sqrt{b} + \sqrt{c} + \sqrt{d} + \sqrt{e} + \sqrt{f} \approx 8.972$ m, where
$a = 1.474^2 - ((1.458 - 1.422) / 2)^2$, $b = 1.473^2 - ((1.418 - 1.376) / 2)^2$,
$c = 1.668^2 - ((1.375 - 1.322) / 2)^2$, $d = 1.447^2 - ((1.326 - 1.274) / 2)^2$,
$e = 1.411^2 - ((1.274 - 1.216) / 2)^2$, and $f = 1.500^2 - ((1.220 - 1.154) / 2)^2$; hypotenuse =
$\sqrt{(\text{true H})^2 + ((\text{bottom diam.} - \text{top diam.}) / 2)^2} = \sqrt{8.9716^2 + ((1.458 - 1.154) / 2)^2} \approx 8.973$ m.

A. Classical Statistical Confidence Interval of the Shaft Height

Using classical statistics to derive a shaft height range from the Tegea drum data is fairly straightforward: the information needed in the calculation is the sample size (number of preserved drums), the population size (original number of drums), the sample mean (average height of the preserved drums), the sample standard deviation, and the *t*-value from the appropriate statistical table. Substituting these into the correct formula, we obtain a 95% confidence interval of 1.458–1.495 m for the drum height. In other words, we can be 95% sure that the mean drum height is between 1. 458 and 1. 495 m, and that the column shaft height is therefore between 8.749 and 8.967 m.[8]

Unfortunately, the matter is not this simple. There are two assumptions which have to be met before classical confidence interval calculation can be used: the sample must be random, and the original population must be normally distributed. Neither of these conditions are fulfilled at Tegea. The preserved drums do not constitute a random sample because neither the choice of the excavated area nor the process of column drum preservation at the site can be regarded as random.[9] We do not know the height distribution of the original drums, but a height histogram of the 60 preserved drums[10] gives some indication (Fig. 20): the clear peak in the middle is caused by *A* and *B* drums which are of uniform height, while the other drums are fairly evenly distributed between the minimum and maximum heights.[11] We have no reason to expect that the original distribution of the drums was much different, since the preserved drums account for 28% of the original number.

Fortunately, in recent years a number of computer-intensive statistical approaches have been developed which are able to deal with non-random and non-normal data. The following three sections show how it is possible to employ two of these, namely bootstrap-*t* and Monte Carlo analysis, in connection with the Tegea column drums.

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[8] The sample mean ($\bar{x}$) is 1.4764 m, the *t*-value corresponding to n–1 degrees of freedom and two-sided γ(=95%) probability level ($t_{\gamma,\, n-1}$) 2.001, the sample standard deviation (s) 0.082748, the sample size (n) 60, and the population size (N) 216. Substituting these into the formula $\bar{x} \pm (t_{\gamma,\, n-1})\, s/\sqrt{n}\sqrt{(N-n)/N}$, we get the 95% confidence interval. For the *t*-value, see Neave 1981, 20, and for the sample size of 60, see n. 10 below. The finite population correction factor can be used in the calculation because the original number of drums is known. On confidence intervals, see e.g. Siegel—Morgan 1996, 321–330 and Shennan 1997, 77–83, and on finite population correction factor, see Shennan 1997, 363–365.

[9] Cf. Shennan 1997, 61: “It is obvious that no archaeological sample can be considered a random sample of what was once present.” See also Edginton 1995, 6–8.

[10] In addition to the 49 complete column drums (see p. 11), there are 11 drums which have the full height preserved; the heights of these drums are underlined in App. A, pp. A9–42.

[11] On the slight skewness of the distribution, see p. 54, esp. n. 16.

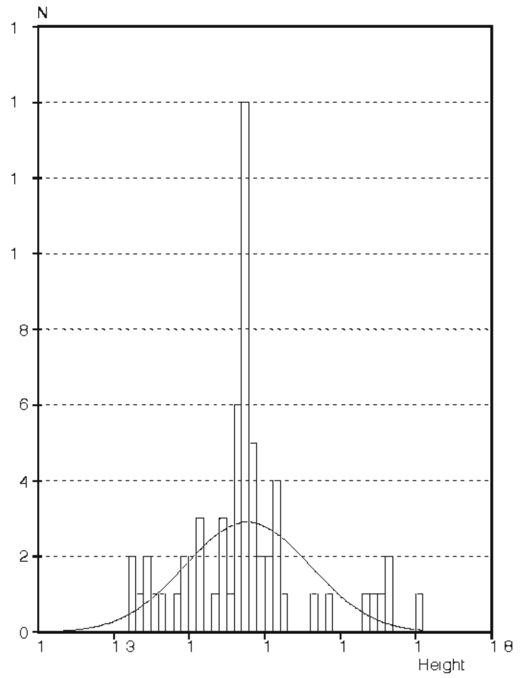

Fig. 20. Histogram of the height of the preserved column drums. N = 60.

B. Bootstrap-*t* Method for Constructing Confidence Interval

The basic principle behind the bootstrap method is that since there is no better knowledge of the population (in this case, all the original temple column drums) than the existing sample, this can be used as a guide to the population distribution. Technically, this involves taking several random resamples of the sample with replacement[12] in order to approximate, in this case, a confidence interval for the drum height. The bootstrap-*t* method was chosen because it does not assume that the population would be normally distributed.[13] The method also gives reasonably accurate results even with small sample sizes, though it should not be used without evaluating its performance; the validity of the bootstrap method is discussed in the next section.[14]

Using the 5000 generated bootstrap values we obtain a 95% confidence interval of 1.460–1.496 m for the drum mean height and of 8.758-8.977 m for the

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[12] After the drum has been selected it is returned to the sample; the probability of it being reselected is the same as the probability of any other drum being selected.

[13] On bootstrap methods, and esp. on the bootstrap-*t* method, see Efron 1981, 152–154, and Manly 1997, 34, 56–59. The technique is called the bootstrap method because it "is supposed to be analogous to someone pulling themselves out of mud with their bootstraps" (Manly 1997, 34). In archaeological contexts, the bootstrap method has not been widely used (for an exception, see Ringrose 1992).

[14] B. F. J. Manly (1997, 58–59) has compared the performance of different bootstrap methods with the small sample size of 20; he emphasizes that "bootstrap methods should be tested out before they are relied upon for a new application".

shaft height.[15] The bootstrap-*t* method defines a range slightly different from the classical statistics range of 8.749–8.967 m: the most probable reason for the difference is the slight skewness of the original drum height distribution (see Fig. 20).[16] The relatively good agreement between a randomisation method and classical statistics is not unexpected, since corresponding cases have often been observed in statistical studies.[17]

C. Monte Carlo Method for Testing Bootstrap Confidence Intervals

Monte Carlo analysis[18] can be used to test the validity of using the bootstrap-*t* method for calculating the confidence interval for the mean drum height. A computer model which can be used to simulate the temple colonnade at Tegea is required. It is possible to implement such a simulation model, as I have demonstrated in a recent paper analysing the preserved drums of the temple of Zeus at Labraunda, Asia Minor.[19]

The computer model, written in C language, can be used to simulate the

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[15] The formula used to calculate the *t*-statistic was $T_B = (\bar{x}_B - \bar{x}) / (s_B / \sqrt{n})$, where $\bar{x}_B$ and s_B are calculated from each bootstrap sample (for $\bar{x}$ and n, see n. 8 above). The minimum of the generated 5,000 t_B values was –3.905 and the maximum 3.189; the values limiting 95% of the distribution were $t_{\alpha/2}$ = 1.846 and the maximum $t_{1-\alpha/2}$ = –2.186. The confidence interval can be calculated as

$$\bar{x} - t_{\alpha/2}\ (s/\sqrt{n}\sqrt{(N-n)/N}) < \mu < \bar{x} - t_{1-\alpha/2}\ (s/\sqrt{n}\sqrt{(N-n)/N}),$$

and we obtain the interval 1.460–1.496 m; since the *t*-statistic T_B was calculated without using the finite population correction factor it is justified to introduce it in the confidence interval calculations (on the factor, see n. 8 above). The random numbers used in the generation of the t_B values are produced with statistical program Survo's *rand*(n_s) function ($1 \leq n_s \leq 2^{32-1}$) using INSEED and OUTSEED specifications (the function has been implemented by S. Mustonen; the numbers are generated according to a Combined Tausworthe generator presented by S. Tetsuoka and P. L'Ecuyer, *ACM Transactions on Modelling and Computer Simulation* 1.2, 1991. The period length of *rand* is about 10^{18}). For the bootstrap-*t* formulae, see Manly 1997, 56–58, and for the program used in the bootstrapping, see App. E, p. E1. The number of generated random values needed in the analysis is discussed in Manly 1997, 80–84.

[16] Skewness of the height distribution is 0.6465.

[17] See e.g. Manly 1997, 16–17. E. S. Edginton (1995, 10–13) emphasises that even though classical statistics and randomisation often produce similar results, the differences show that the consideration of the validity of the method used is also a practical issue.

[18] The use of Monte Carlo methods in archaeology is not very common: P. Fisher *et al.* (1997, 584–585) give a list of archaeological studies which have employed Monte Carlo analysis, and they regret that the method "is not even mentioned by many texts in archaeological statistics"; to their list can be added a paper by B. F. J. Manly (1996), and that in the second edition of his textbook, S. Shennan (1997, 64) discusses Monte Carlo testing briefly. On Monte Carlo methods in general, see e.g. Manly 1997, 69–78.

[19] See Pakkanen 1998; the computer programs used for simulation in the paper were originally programmed for the purposes of the Tegea study, but the results of the Labraunda temple study were first in print.

process of first building the temple columns, then their partial destruction, and finally the scholar's attempt to reconstruct the shaft from the remaining drums. The information input to the program is as follows: lower and upper diameter of the shaft, range of the lower diameters, column height, the amount and height of the maximum entasis, number of columns on front and flank, number of drums in one column, minimum and maximum height of each course of drums, number of preserved drums, and accuracy of taken measurements. The program uses this information to build up the column shafts, all of them randomly slightly different. The selection of the 'surviving' drums is also random. The last phase of reconstructing the possible shaft combinations is not used in the Monte Carlo analysis: only the generated drum height data is used to determine whether the shaft height given as a parameter to the program falls within the defined bootstrap intervals.[20]

Since the exact height of the column shaft is unknown, the bootstrap-*t* confidence interval of 8.76–8.98 m was taken as the starting point of the simulations: beginning with a shaft height of 8.76 m, the process of building the colonnade and defining a bootstrap confidence interval for the mean shaft height was repeated 84 times for each height at two centimetre intervals, so that the total number of simulations was 1,008.[21] The height ranges of each course of drums were given as follows: *A* drums, 1.46–1.48 m; *B* drums, 1.46–1.49 m; and *C–F* drums, 1.30–1.73 m.[22] The confidence interval was defined by randomly selecting 60 drums; based on these drums the interval was calculated by producing 1,000 bootstrap values.

The result of the 1008 simulations is that in 955 cases (94.7%) the original shaft height is within the obtained 95% bootstrap confidence interval. The discrepancy between the expected confidence level of 95% and the obtained level of 94.7% is very small, and it may, therefore, be concluded that the bootstrap method is a valid method for determining the shaft height at Tegea.

D. Monte Carlo Test for Confidence Intervals and Non-random Data

The computer model described above can also be used to simulate the effect of non-random data on the column shaft height distribution. The simulation is done by reducing the number of columns given as a parameter to the program: if the 60 preserved drums were originally from ten columns of six drums each, we would have the complete population accounted for, so that the mean drum height multiplied by six would accurately give the shaft height. The degree of randomness can be increased by increasing the column-number parameter: the simulation was started with 12 columns, and continued at an interval of two, until 36, the number

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[20] On the computer program, see App. E, p. E1.

[21] 84 colonnades of 8.76 m, 84 colonnades of 8.78 m, etc. until 8.98 m was reached; $12 \times 84 = 1{,}008$.

[22] For the height ranges of the preserved drums at the site, see p. 22. The shapes of the random drum height distributions created using these ranges are very similar to the drum height distribution shown in Fig. 20.

of columns in the temple, was reached. With 36 columns the simulation is comparable to a completely random situation. The testing was done by determining how frequently the original shaft height falls within the classical 95% confidence interval calculated from the randomly selected 60 drums.[23] The classical confidence interval was used in the tests because it requires only a fraction of the calculations needed to determine the bootstrap interval. The simulation was executed 1,008 times for each number of columns.[24] The results of the simulations are summarised in Table 6.

Table 6. Effect of non-random data on confidence interval.

Number of columns	*Within limits (f)*	*Within limits (%)*
12	1,008	100.0
14	1,004	99.6
16	1,000	99.2
18	998	99.0
20	992	98.4
22	987	97.9
24	985	97.7
26	973	96.5
28	967	95.9
30	965	95.7
32	966	95.8
34	967	95.9
36	957	94.9

Even though the fairly small number of simulations does not produce an absolutely smooth change, the trend in the coverage of the confidence interval is clear: the more random the selection of column drums, the less often the column shaft height falls within the limits of the 95% classical confidence interval. When the simulation corresponds to a completely random situation, the classical and Monte Carlo intervals converge. Therefore, the use of confidence intervals can be justified in this instance: even if the drums discovered at Tegea were from a limited number of columns and as such constituting a seriously non-random sample, the confidence interval will give a conservative estimate of the shaft height range.

In the next sections, the possibility of defining the shaft height range more accurately than the statistical confidence interval is surveyed: the key factor in this process is determining certainly matching pairs of column drums at Tegea.

[23] In order to demonstrate the effect of non-randomness, the population size N was kept as $36 \times 6 = 216$ in the confidence interval calculations; for the formula, see n. 8 on p. 52.

[24] The simulated heights were 8.76–8.98 at 2 centimetre intervals, and the number of simulations for each height was 84 ($12 \times 84 = 1,008$).

Table 7. Probability of matching pairs of column drums at Tegea.

n	*A & B*	*B & C*	*C & D*	*D & E*	*E & F*
0	0.04146	0.00772	0.07880	0.18697	0.24388
1	0.19349	0.06173	0.27580	0.39833	0.42678
2	0.33605	0.19097	0.35460	0.29875	0.25607
3	0.28004	0.29955	0.21491	0.09958	0.06566
4	0.12002	0.26211	0.06541	0.01532	0.00730
5	0.02619	0.13243	0.00981	0.00102	0.00031
6	0.00266	0.03863	0.00065	0.00002	0.00000
7	0.00009	0.00631	0.00001	0.00000	
8		0.00054			
9		0.00002			
10		0.00000			
1 or more	0.95854	0.99228	0.92120	0.81303	0.75612

E. Probability of Matching Column Drums at Tegea

Calculating the mathematical probability of matching pairs of column drums will give some suggestions of what kinds of results might be expected with the excavated material. With 49 of the original 216 drums the probability of a complete shaft being preserved at Tegea is very small, only 0.4%.[25] However, the chances of discovering individual matching pairs is very high. The probability of the number of matching pairs is summarised in Table 7. The last line gives the sum of one or more matching pairs. For example, the probability of discovering one matching pair of *C* and *D* drums at Tegea is 27.6%, while the probability of discovering *at least* one pair is as high as 92.2%.

F. Matching Drums

The study of matching drums at Tegea involved several different phases. In the first place, the schematic drawings of empolion cuttings and dowel holes were copied from zone sheets to transparent draft papers.[26] The drums that could, on the basis of their diameter measurements, be matching are listed in Appendix A (pp. A60–61), and using this list as a guide, the possibly matching pairs were

[25] The following iterative formulae for calculating the probability have been derived by S. Mustonen:
Let P(k,h) be the probability that on level k there are h preserved complete columns.
If $k = 1$ then if $h = n_1$ then $P(k,h) = 1$ else $P(k,h) = 0$.

$$\textbf{If } k > 1 \textbf{ then } P(k,h) = \sum_{j=h}^{n_{k-1}} \left[P(k-1,j) \binom{j}{h} \binom{n-j}{n_k-h} \Big/ \binom{n}{n_k} \right].$$

At Tegea the numbers of preserved drums on each level are $n_1 = 7$, $n_2 = 12$, $n_3 = 10$, $n_4 = 7$, $n_5 = 7$, and $n_6 = 6$, and the number of columns $n = 36$. The probability of one or more complete columns being preserved can be calculated as $1 - P(6,0) \approx 0.00408$. The calculations were performed using editorial arithmetics in the statistical program Survo.

[26] Copies of these are in App. A, pp. A43–59.

checked from the drawings. For example, the upper faces of *A* drums were compared with the lower faces of *B* drums; for the comparison, the sheet for *B* drums must be turned upside down in order to imitate the situation with real drums. This procedure was followed through for all the possible matching drums. The information gathered during the process is typographically coded in the list of matching drums.

The placement of the empolion and dowels was confirmed to be characteristic of each block: the distance between the cuttings and their orientation compared to flutes and to each other varies considerably; also the dowels are quite often asymmetrically placed on the two sides of the empolion. Three pairs of drums were discovered to be matching according to the 1:25 drawings.[27] In addition to these, five pairs were discovered to be possible matches, but they had the other or both surface drawings incomplete with, for example, only one dowel hole.

When the three matching drum pairs were rechecked and drawn at a scale of 1:10 in 1995, only one pair was found to actually match: the pair consisting of a *D* drum 35 and an *E* drum 115. The upper surface of block 35 is shown in Figure 21 and the lower surface of block 115 in Figure 22.

A different method for determining matching pairs of drums was experimented with in 1998: the flute widths were measured with a special instrument and the slightly varying flute width sequences of different drums were compared. A new pair comprising of a *C* drum 9 and a *D* drum 7 was discovered: the drums are located on the temple foundations very close to each other. The pair was originally missed because the top surface of the *C* drum and the bottom of the *D* drum are currently against the foundations and only partially visible.[28] The flute width sequences of the two matching pairs are presented in Table 8. Since the edges of the surfaces were largely broken on all the blocks, the flute width measurements are taken at ca. 0.20–0.30 m above or below the joint; the flute widths are, therefore, listed as differences of the mean value (the range is –1 – +2 mm). The flute widths of blocks 35 and 115 overlap for six flutes, and only one of the overlapping flutes can be measured accurately on both of the drums. The result of the flute width comparison is more reliable in the case of the second matching pair of drums: the measurements can be taken for 17 overlapping flutes, and of the six flutes which it was possible to measure accurately, only one shows a discrepancy of 0.5 mm. All the other flutes match within the measurement accuracy.

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[27] The corners of the empolion cuttings would not have to coincide exactly due to the construction of the empolion: the small square wooden blocks are only needed to hold the centring pin. But since matching empolion cuttings produced good results at Nemea, where there are no dowels, this method was also adopted at Tegea. On Nemea, see Cooper—Smith 1983, 63–64.

[28] On the basis of the positions of the visible dowel holes and the empolion cuttings the two drums could be matching.

Table 8. Flute width sequences of the matching pairs of drums.

35	–	(0)	(0)	(0)	+1	(+1)	(0)	+1	+1	0	+1	0	(+1)	(+1)	–	–	–	–	–	–
115	(–1)	(0)	(0)	–	–	–	–	–	(+1)	(–1)	+1	(0)	(0)	(0)	0	(0)	(0)	(+1)	(0)	0
9	(0)	(0)	–1	+1	0	0	+1	+1	(0)	0	+1	0	+1	(0)	(+1)	0	(0)	0	0	0
7	0	0	–0.5	(+1)	(0)	0	(0)	(+1)	(0)	0	(0)	0	+1	+1	(+2)	0	+1	–	–	–

The measurements of the same flute are listed one above the other. The parentheses denote flutes with partially broken arrises indicating a possible discrepancy of ± 1 mm with the given figure.

G. Height of the Column Shaft

Using the pairs of column drums ascertained above it is possible to attempt to define the shaft height more accurately than the 95% confidence interval. Since the shaft height is partially determined by the matching pairs, determination of the confidence interval is only necessary for the rest of the shaft: taking the pair comprising the blocks 35 and 115 (*D* and *E* drums), the 95% bootstrap-*t* confidence interval for the mean height of *A, B, C,* and *F* drums can be determined as 1.454–1.493 m and for the shaft height as 8.891–9.046 m.[29] The difference between this confidence interval and the previously determined bootstrap interval of 8.758-8.977 m is due to the matching pair being slightly taller than the average drums. Cutting the non-overlapping tails off, it is possible to establish the new limits as 8.891 and 8.977 m.

The procedure can be repeated for the second pair of blocks 9 and 7 (*C* and *D* drums). The confidence interval for the mean height of *A, B, E,* and *F* drums is 1.442–1.482 m and for the shaft height 8.952–9.111 m.[30] Both of the drums in this pair are significantly taller than average drums, so the limits of the confidence interval are also greater than the previously defined limits. In fact, the intervals have an overlap of only 2.5 cm, thus allowing the shaft height to be determined as 8.952–8.977 m at a confidence level of 95%. The bootstrap confidence interval of the mean capital height is 0.592–0.603 m,[31] so that the confidence interval of the

[29] The minimum of the generated 5,000 bootstrap *t*-values was –3.7938 and the maximum 3.8287; the values limiting 95% of the distribution were $t_{\alpha/2} = 1.976$ and $t_{1-\alpha/2} = -2.101$. Other variables substituted into the confidence interval formulae of n. 15 (p. 54) above were $\bar{x} = 1.4733$, $s = 0.070907$, $n = 40$, and $N = 4 \times 36 = 144$. The minimum of the shaft height range was calculated as follows: 1.493 [height of block 35] + 1.580 [height of block 115] + (4 × 1.4544) ≈ 8.891 m; the maximum: 1.493 + 1.580 + (4 × 1.4933) ≈ 9.046 m.

[30] The minimum of the generated 5,000 bootstrap *t*-values was –3.9087 and the maximum 3.5060; the values limiting 95% of the distribution were $t_{\alpha/2} = 2.016$ and $t_{1-\alpha/2} = -2.093$. Other variables substituted into the confidence interval formulae of n. 15 (p. 54) above were $\bar{x} = 1.4619$, $s = 0.070993$, $n = 39$, and $N = 4 \times 36 = 144$. The minimum of the shaft height range was calculated as follows: 1.668 [height of block 9] + 1.514 [height of block 7] + (4 × 1.4424) ≈ 8.952 m; the maximum: 1.668 + 1.514 + (4 × 1.4823) ≈ 9.111 m.

[31] The minimum of the generated 5,000 bootstrap *t*-values was –14.067 and the maximum 4.2657; the values limiting 95% of the distribution were $t_{\alpha/2} = 1.9089$ and $t_{1-\alpha/2} = -3.2667$. Other variables substituted into the confidence interval formulae of n. 15 (p. 54) above were $\bar{x} = 0.5961$, $s = 0.007978$, $n = 10$, and $N = 36$.

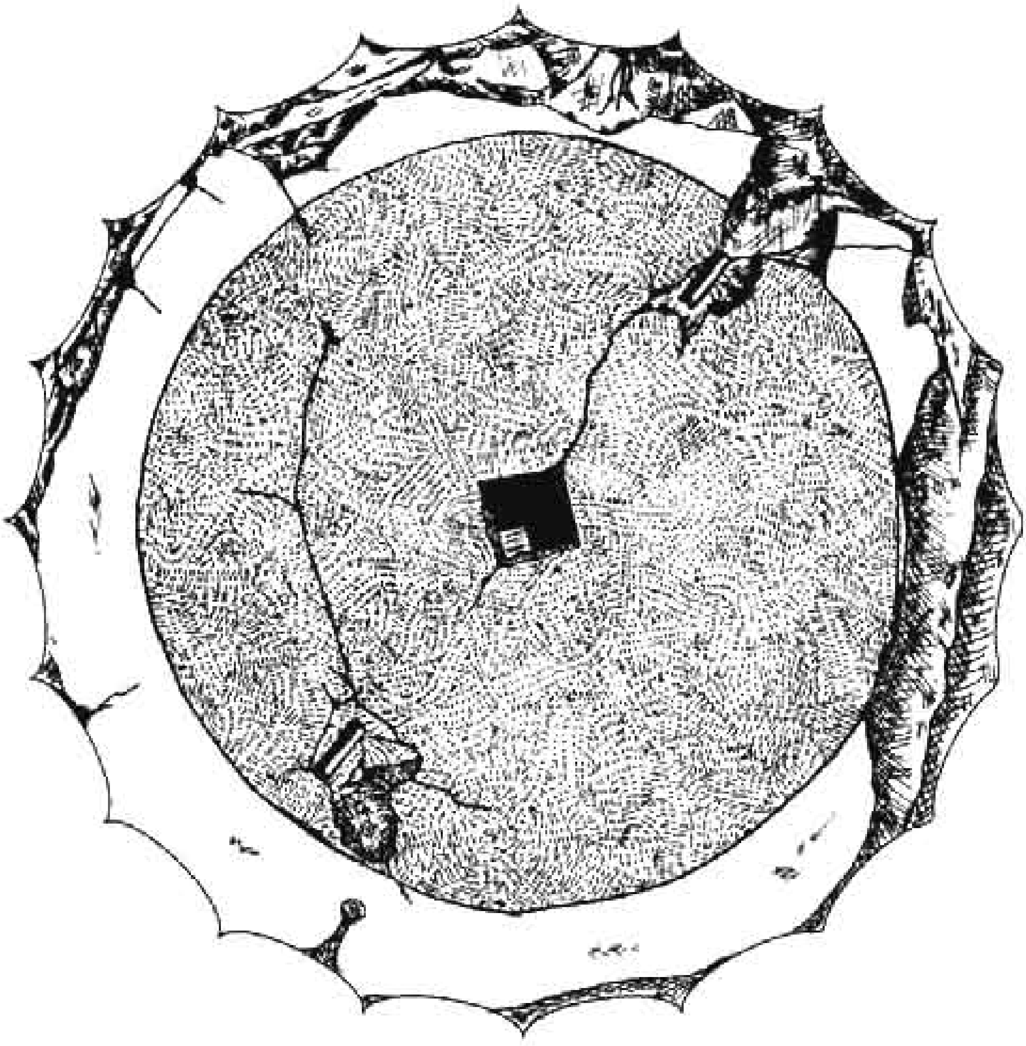

Fig. 21. Upper surface of block 35. Scale 1:10

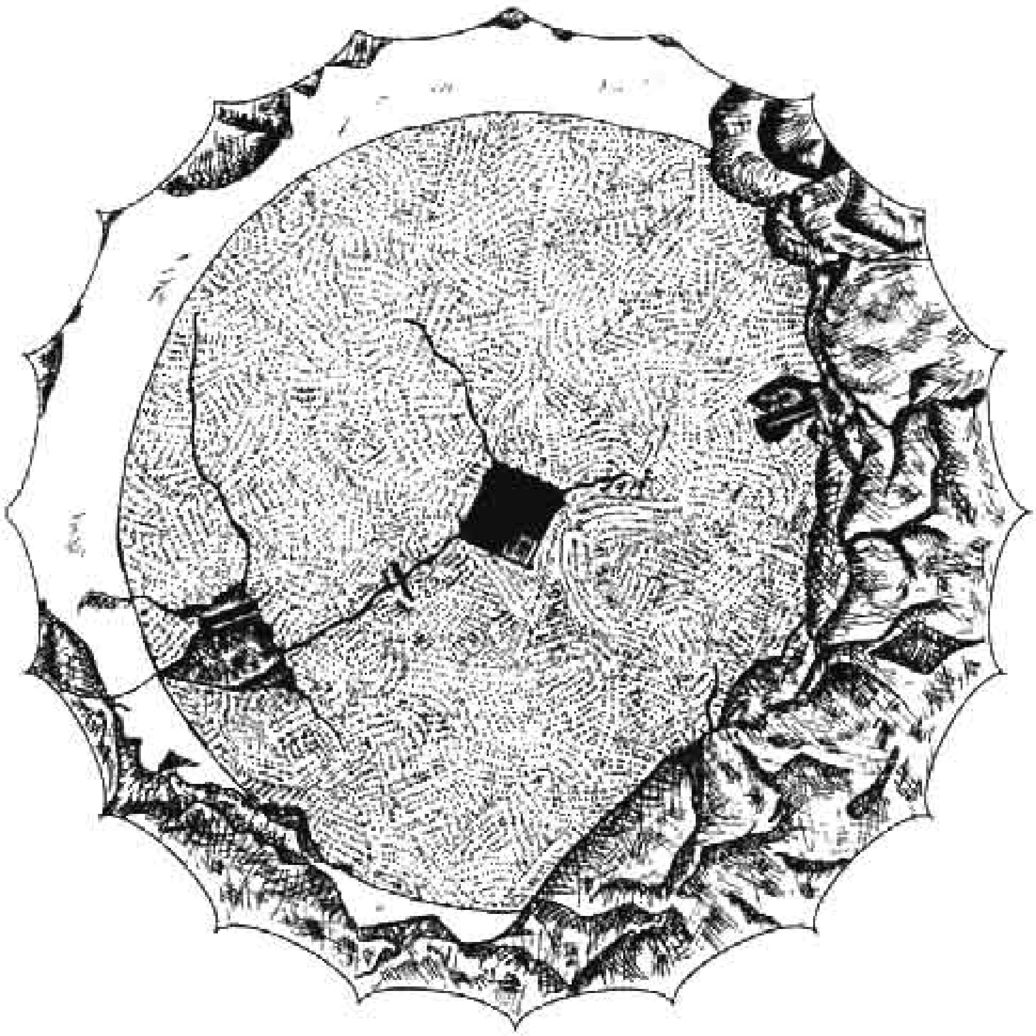

Fig. 22. Upper surface of block 115. Scale 1:10.

whole column height with the capital is 9.544–9.580 m.[32]

3. The Shaft Profile

As we saw in the previous section, the height of the column shaft can be quite accurately determined. Another important feature of the shaft, entasis, is discussed in the following sections.

A. Possible Combinations of the Column Drums

During the documentation project of the drums an error margin particular to each measurement was determined.[33] When the computer program which combines the drums according to diameter measurements and measurement margins is run with the new data as input, the result is quite similar to a run using Clemmensen's data: the histogram of the possible column shaft combinations for the old data is presented in Figure 1 and for the new data in Figure 23.[34] The distribution in the latter is more clearly trimodal with one main and two subsidiary modes. The peak of the main mode is at 8.77–8.81 m, at a slightly lower height than Clemmensen's first cluster of 8.80–8.85 m, but the second peaks coincide at 8.95–8.98 m. The second peak—shaded darker than the rest of the distribution—also corresponds to the shaft height defined in the previous section. Due to more measured drums and to some wider measurement margins, the number of possible combinations has exploded from 3,361 to 27,516. The number of possible shaft combinations within the range 8.952–8.977 m is 1,678.

B. Shaft Profiles and Maximum Entasis

Measurement accuracy is an important factor in determining which of the possible drum combinations constitute acceptable shaft profiles. The average accuracy of

[32] Independently of the statistical confidence interval of the mean shaft height, I have argued for a column height of 9.56–9.58 m based on the cella wall; however, there is no question that the height analysis presented here is a better solution to the problem and should be preferred over the analysis in Pakkanen 1996b, 163–164. Moreover, it is very probable that an analysis of the cella wall height will not make it possible to define the temple height any more accurately than on the basis of the column height; even if it is possible to determine the sequence of cella wall blocks of different heights with certainty, the variation in the heights of the courses easily amounts to three or four centimetres.

[33] See p. 12, esp. n. 6.

[34] On the computer program, see p. 2 and App. E, p. E2; for a discussion of Fig. 1, see pp. 2–3. Blocks 48 and 93, both *A* drums, are omitted from the possible shaft combinations because their lower diameter can only be estimated.

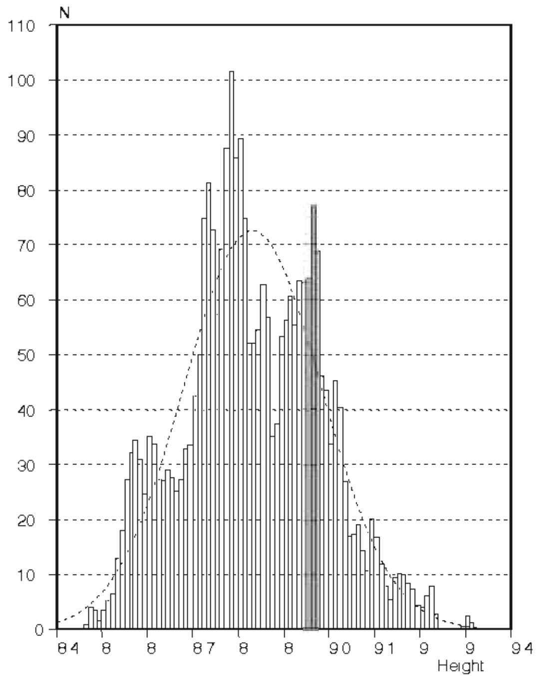

Fig. 23. Histogram of possible shaft height combinations: N = 27,516. Based on new measurements.

the column drum diameter measurements at Tegea is ±2.9 mm (for the measurement ranges, see Appendix A). In the profile analysis the radii of the drums are used rather than the diameters, so the level of accuracy must also be halved: for a measurement margin of ±2.9 mm the parameter of accuracy can be input as ±1.5 mm to the computer program used in the analysis.

It is possible to determine which of the drum combinations at Tegea produce a consistent shaft profile within the measurement accuracy by employing a computer program[35] which defines two boundary lines for each combination: all the points of the shaft profile should fall within these two lines to be accepted as a possible solution. Figure 24 presents an acceptable drum combination: all the small circles representing the shaft co-ordinates are within the zone defined by the dotted lines. Figure 25 shows an unacceptable profile where the point at the joint of the first and the second drum falls outside the zone.

The curves of the boundary lines are parabolas, and their position is defined by the measurement accuracy parameter and the position of the maximum entasis input to the computer program. The curve on the left is 1.5 mm to the left of the "ideal" shaft profile, and that on the right is the same amount to the right (see Figs. 24 and 25). The width of the complete zone is in this case ±1.5 mm.

For the starting point of the analysis, a data-file including the shaft co-ordinates of the 1,678 possible shaft combinations within the shaft height range of 8.952–8.977 m was created. The computer program was run with different parameters for the height of maximum entasis (at 40–60% of the shaft height) and

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[35] See App. E, pp. E2–3; on the use of the same computer program in connection with Labraunda, see Pakkanen 1998.

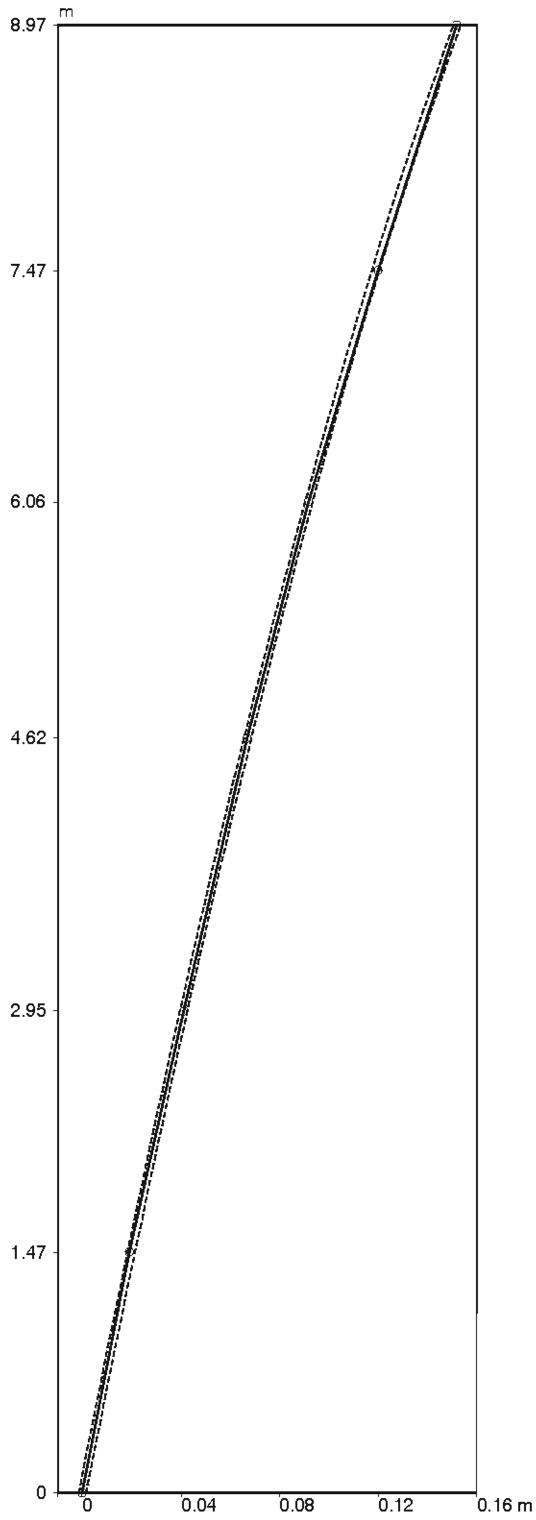

Fig. 24. Example of acceptable shaft profile.

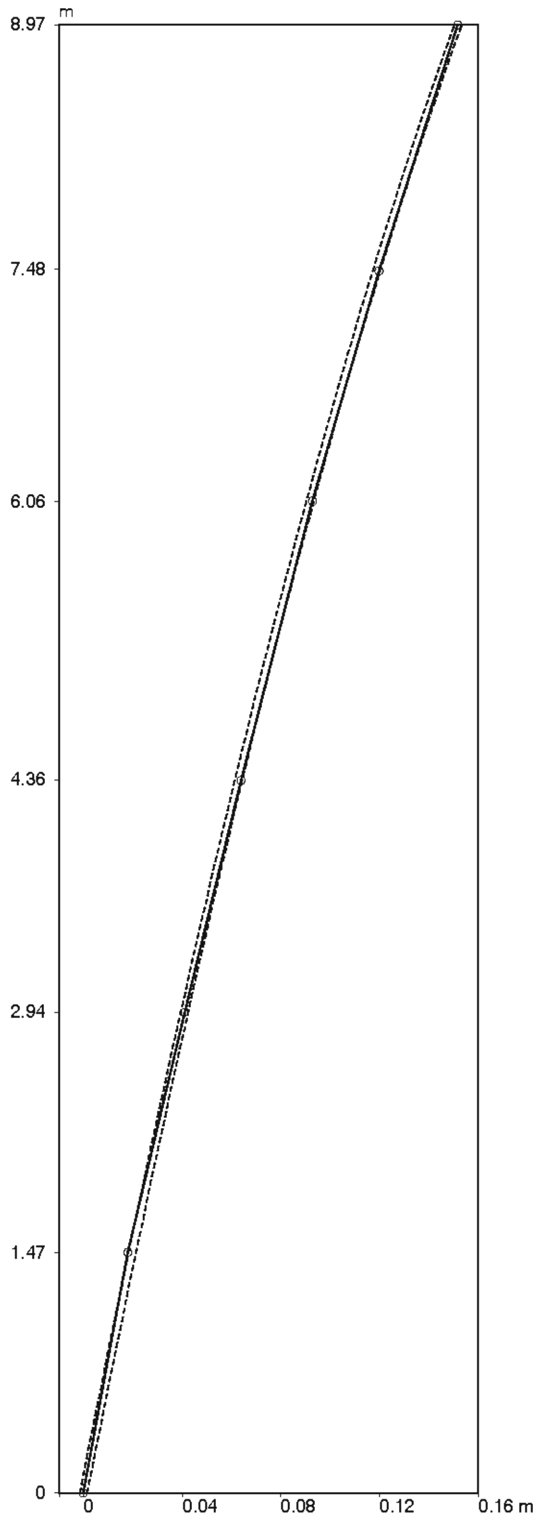

Fig. 25. Example of unacceptable shaft profile.

Table 9. Frequencies of accepted shaft profiles.

	13 mm	12 mm	11 mm	10 mm	9 mm
0.60	42	88	**137**	82	66
0.59	42	87	119	81	62
0.58	42	88	113	79	61
0.57	42	88	111	77	62
0.56	40	88	116	77	62
0.55	37	89	**126**	79	62
0.54	35	89	**139**	81	61
0.53	25	87	**149**	82	61
0.52	23	81	**150**	82	65
0.51	18	84	**151**	79	66
0.50	20	77	**152**	69	65
0.49	20	68	**146**	70	63
0.48	20	70	**144**	82	66
0.47	19	66	**130**	84	42
0.46	10	61	**127**	89	31
0.45	11	50	114	83	38
0.44	11	43	93	88	44
0.43	8	25	90	98	47
0.42	8	19	87	96	59
0.41	5	20	81	**148**	59
0.40	4	13	70	**152**	80

The top row gives the amount of maximum entasis and the left column the proportional height of maximum entasis.

the amount of maximum entasis (9–13 mm). The values of these parameters were based on preliminary analysis and architectural comparanda: Varying the amount of maximum entasis, there are very few acceptable shaft profiles below 9 mm and above 13 mm. In Late Classical Doric architecture in the Peloponnese and at Delphi the position of maximum entasis is invariably approximately in the middle of the shaft.[36] All the 1,678 shaft profiles were tested, for all the different combinations of input parameters, for whether they produce an acceptable within the measurement accuracy or not: the frequencies are summarised in Table 9. The darker the background colour, the more acceptable shafts there are in the class. For example, with the amount of maximum entasis set as 12 mm and the height of entasis as 0.46, of the 1,678 possibilities 61 fall within the zone of conceivable profiles.

There are two clusters with high frequency of acceptable shaft profiles: the first one has a maximum entasis of 11 mm at the height of 48–53% of the complete shaft and the second has a maximum entasis of 10 mm at 40–41% of the shaft. Comparative material would suggest that the first cluster is the more probable position of maximum entasis,[37] and this is confirmed by calculating the means of the x and y co-ordinates of the 1,678 possible shaft profiles: the amount of maximum entasis of the mean profile is 11 mm at 48% of the shaft height. This

[36] At 48–56% of the shaft height (Pakkanen 1997, 342, table 3).

[37] See n. 36 above.

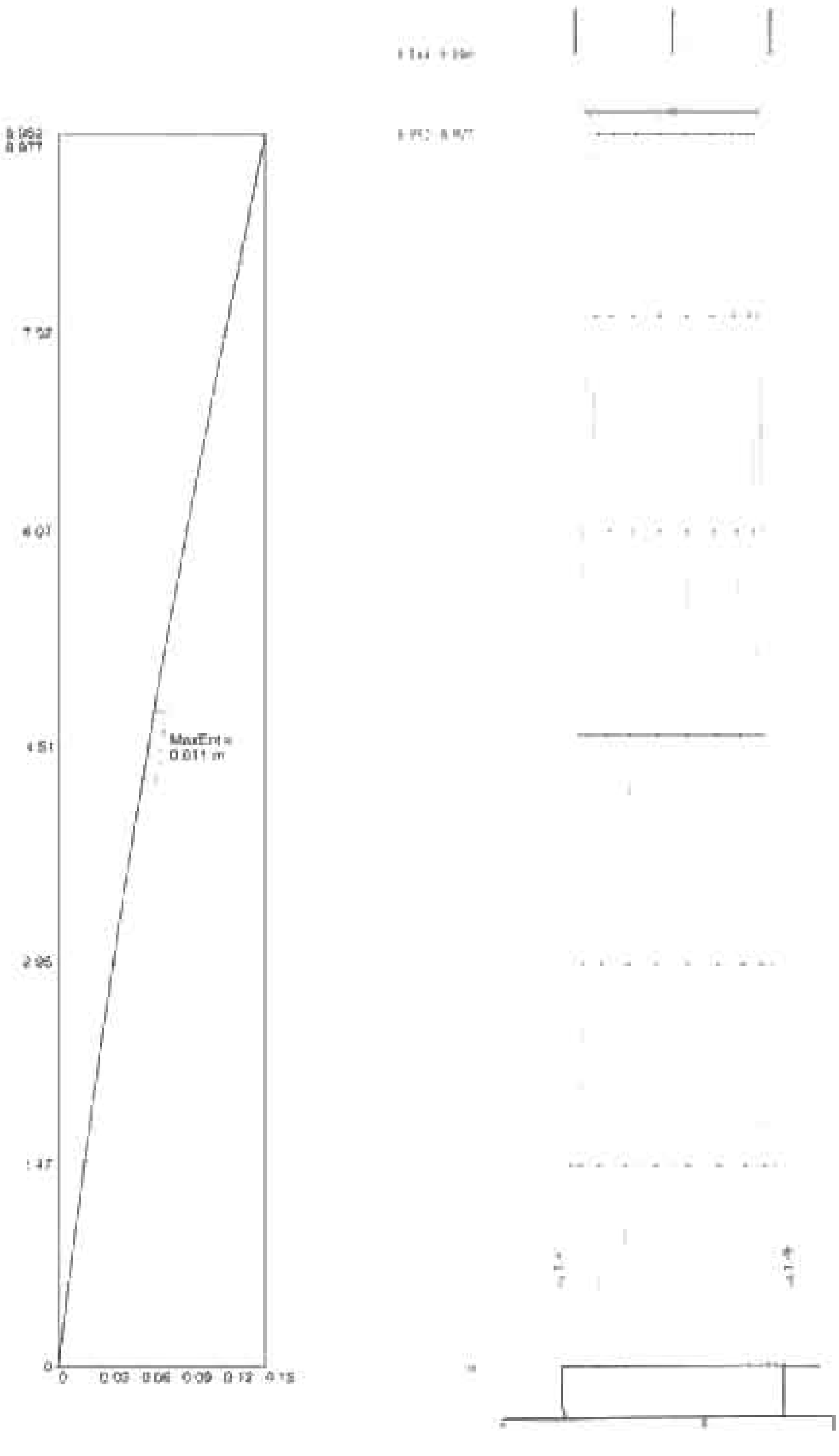

Fig. 26: Shaft profile with exaggerated *x* axis (left); reconstruction of the peristyle column (right; scale 1:50).

shaft profile is presented in Figure 26; the change in the direction of the entasis curve is minimal in the middle of the shaft, such that it is preferable to give the height of the maximum entasis as within the range 48–53% rather than selecting a single value for it.[38] The right part of Figure 27 shows a reconstruction of the peristyle column at Tegea.

4. Shaft Design

A. Foot Unit

I have intentionally refrained from making any references to ancient foot units in the previous analysis: the measurement ranges have been determined using statistics and various computer programs. Table 10 displays the main dimensions of the column, and they are compared to a number of foot units proposed by different scholars. H. Bankel has tentatively suggested an 'Ionic foot' of 0.294 m, H. Bauer a unit of 0.296 m, Ch. Dugas, M. Clemmensen, and W. Koenigs a unit of 0.2985 m, and finally W. B. Dinsmoor a 'Doric foot' of 0.326 m.[39]

Table 10. Dimensions expressed in different foot units and their discrepancies.

M	*Min*	*Max*	*Bankel*	*Discr*	*Bauer*	*Discr*	*Dugas*	*Discr*	*Dinsm*	*Discr*	0.3065	*Discr*
$Diam_{LA}$	1.545	1.554	5'4"	–0.001	5'4"	–	5'3"	–	4'12"	–	5'1"	–
$Diam_{UA}$	1.196	1.213	4'2"	–	4'1"	–	4'1"	–	3'11"	–	3'15"	–
ColH	9.544	9.580	32'8"	–	32'4"	–	32'0"	–	29'6"	–	31'4"	–
ShaftH	8.952	8.977	30'8"	–	30'4"	–	30'0"	–	27'8"	–	29'4"	–
CapH	0.592	0.603	2'1"	0.003	2'0"	–	2'0"	–	1'13"	–0.001	1'15"	–
AbW	1.609	1.616	5'8"	0.001	5'7"	–	5'6"	–0.005	4'15"	–	5'4"	–

If the measurement expressed as feet and dactyls falls within the measurement range, no discrepancy is reported, and if it does not, the distance to the closest limit is reported as the discrepancy: for example, a discrepancy of –0.001 m in Bankel's lower shaft diameter means that 5'4" (≈ 1.544 m) is actually 0.001 m below the lower limit of the measurement range. As we see, the different foot measures generally fit very well within the established ranges, and even though there are no discrepancies with Bauer's foot unit of 0.296 m, I would hesitate to prefer it to the others because of the very small discrepancies observable in the other proposals. It is actually possible to find a number of completely hypothetical 'foot units' that fit to the ranges without any discrepancies; in Table 10 a unit of 0.3065 m is given as an example. However, it is interesting that the column and shaft

[38] The plotted points in Fig. 26 are (0,0), (0.018,1.471), (0.040,2.947), (0.065,4.502), (0.093,6.072), (0.121,7.523), (0.150,8.964), and the formula of the fitted curve is $y = 0.005 + 82.3x - 235.5x^2 + 562.4x^3$.

[39] Bankel 1984, 415; Bauer 1973, 69; Dugas *et al.* 1924, 59; Clemmensen 1924, 10; Koenigs 1977, 231–233; Dinsmoor 1950, 195 n. 1, 219.

heights can be expressed in feet and simple fractions of a foot in four of the systems: the column height could be 32½ and the shaft height 30½ 'Ionic feet' of 0.294 m, or 32¼ and 30¼ Bauer's foot units of 0.296 m, or 32 and 30 Dugas' foot units of 0.2985 m, or 31¼ and 29¼ feet of 0.3065 m. In conclusion, it seems that no decision on the ancient foot unit used in the design of the temple of Athena Alea at Tegea can be made on the basis of the column measurements.

B. Drum heights

It was recently suggested to me by M. Korres that one possible explanation for the differing heights of the *C, D, E,* and *F* drums could be that the *C* and *D* drums on the one hand, and the *E* and *F* drums on the other hand, were designed as pairs so that the height of the joint of *D* and *E* drums was constant. This suggestion, however, does not seem to be supported by the possible drum combinations with the known pairs of matching drums. In the shafts comprising the matching *C* drum 9 and *D* drum 7 the top surface of the *D* drum is at a height of 6.12–6.14 m, and in the shafts with matching *D* drum 35 and *E* drum 115 the joint between the drums is at a height of 5.91–6.07 m.[40] Since these ranges do not overlap, the placing of the tall and short drums within the shaft appears not to have been systematic.

C. Entasis Design

I have discussed entasis in fourth-century BC Doric buildings in the Peloponnese and at Delphi in a recent article:[41] the data presented in Table 11 conforms well to the conclusions of that text. On the basis of the figures in Table 11 it is possible to evaluate how well the conic sections—circle, ellipse, parabola and hyperbola—fit to the shaft profile measurements.[42] The residual sum of squares is calculated by squaring the differences between the *y* co-ordinates and the predicted values of *y* and then adding these together. On the basis of the mean of the absolute discrepancies it is possible to evaluate the accuracy of the estimated curve: for example, with the circle formula the measured heights are on average at a distance of 26 mm from the calculated shaft profile *y* co-ordinates.

All the different conic sections fit to the shaft profile data very accurately. If Skopas used a conic section in the design of the shaft profile, it is reasonable to suggest that he would have employed a circle or an ellipse, as they are easier to

[40] The number of shaft combinations within the height range 8.952–8.977 m for the matching *C* and *D* drums is 97, and for the matching *D* and *E* drums it is 18.
[41] Pakkanen 1997.
[42] For the co-ordinates of the fitted shaft profile, see n. 38 above. On curve fitting and entasis in general, see Pakkanen 1997, 336–341.

Table 11. Mathematical formulae and their fit to points of the Tegea shaft profile.

Building and fitted formula	Residual sum of squares	Mean of absolute discrepancies (m)
Circle: $(x-x_0)^2+(y-y_0)^2=r^2$ $x_0 = 947.328$ (0.009), $y_0 = -11.461$ (0.059), $r = 947.328$ (0.009)	0.0102	0.030
Ellipse: $\frac{(x-x_0)^2}{a^2}+\frac{(y-y_0)^2}{b^2}=1$ $x_0 = 2.983$ (–), $y_0 = -12.868$ (0.952), $a = 3.0606$ (0.0075), $b = 57.604$ (1.714)	0.0040	0.023
Parabola: $(y-y_0)^2 = a \times (x-x_0)$ $x_0 = -0.06948$ (0.00613), $y_0 = -11.4564$ (0.7467), $a = 1893.99$ (88.44)	0.0034	0.021
Hyperbola: $\frac{(x-x_0)^2}{a^2}-\frac{(y-y_0)^2}{b^2}=1$ $x_0 = 0.7700$ (–), $y_0 = -7.7277$ (0.3579), $a = 0.7235$ (0.0034), $b = 21.227$ (0.214)	0.0025	0.015

The standard errors of the estimated parameters are given in the parentheses.[43]

use than a parabola or a hyperbola. In the following I will present two possibilities for how the architect could have designed the gently curving profile.

Producing a scale drawing of a polygon approximating an arc of an ellipse is quite simple.[44] All that is required are a ruler with dactyl markings and a drawing surface of ca. 0.20 × 0.60 m. Let us hypothetically suppose that Skopas was using Dugas' foot unit of 0.2985 m in the design: the shaft height expressed in feet would in that case be 30 feet, and the taper of the profile half a foot or eight dactyls.[45] I am intentionally using here values calculated from the shaft diameters measured between the flutes and not the arrises, because this makes it possible to compare the measurements derived from the drawing with dimensions of the shaft profile: I am not suggesting that the architect actually designed the profile of the flute bottom instead of the arris.

In the scale drawing the width of the area, eight dactyls, is marked at full scale, but the height is scaled down: one dactyl corresponds to one foot and the height of the drawing is 30 dactyls. If the architect is of the opinion that dividing

[43] No standard error is given for parameter x_0 of the ellipse and the hyperbola because it is given as input to the program which estimates the other parameters; see Pakkanen 1997, 338 n. 79.

[44] I wish to thank M. Korres for several discussions on curvature design: I have greatly benefited from his insights. Even though no Late Classical scale drawings are known, there is a mid-third-century drawing of a shaft profile on the cella wall of the Ionic temple of Apollo at Didyma; see Haselberger 1983, 115–121.

[45] The lower diameter of the shaft between flutes expressed in Dugas' feet is 4'14" and the upper diameter 3'14"; the difference, 16", must be halved in order to get the taper of the profile, 8".

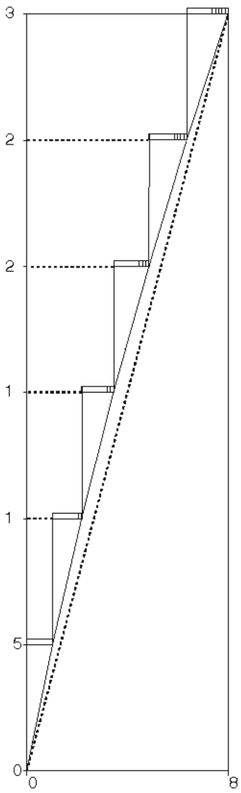

Fig. 27. Hypothetical design drawing of the shaft profile. Dimensions in dactyls.

the shaft height into six equal parts—six is also the number of drums in the shaft—is enough, the ruler must have one of the dactyl markings divided into eight equal parts. The method of drawing the polygon is illustrated in Figure 27. The first point is marked at five dactyls above the base line and one dactyl to the right of the vertical line. From this point another vertical line is drawn to ten dactyls and the next point is marked one dactyl and one subdivision to the right of the new vertical. Again, a new vertical is drawn from this point, but at 15 dactyls the offset to the right is now one dactyl and two subdivisions. At 20 dactyls the offset is increased to one dactyl and three subdivisions, and at 25 dactyls the offset is one dactyl and four subdivisions; at 30 dactyls, or at the top of the drawing, the new point set at one dactyl and five subdivisions to the right of the previous point is very nearly eight dactyls to the right of the first vertical line (the discrepancy is 2 mm). After the marked points are connected, the amount of shaft taper can be measured from the drawing for any given height. No difficult calculations are necessary at any stage of the method.[46]

The discrepancies between the x co-ordinates of the above presented

[46] Anyhow, it is possible to derive a formula for determining the x co-ordinates of the polygon when y is divided into k equal parts:

$x(0) = 0$; $x(1) = d$; for $\underset{2}{\overset{k}{n}}$ $x(n) = nd + \mathrm{m}(n) \times d \,/\, a$, where $\mathrm{m}(n) = \sum_{i=1}^{n-1} i$ and, in this case, $d = 1$ dactyl and $a = 8$.

Table 12. Comparison of different methods of deriving the *x* co-ordinates of the shaft profile (m).[47]

Shaft height	*Design drawing*	*Estimated circle*	*Unit of* 0.3065 m
5 ft.	0.019	0.019	0.019
10 ft.	0.040	0.041	0.041
15 ft.	0.063	0.065	0.065
20 ft.	0.089	0.091	0.091
25 ft.	0.117	0.120	0.120
30 ft.	0.147	0.151	0.151

graphical method and the true circle fitted to the measurement data are small but noticeable (Table 12).[48] If in the design drawing a 'foot unit' of 0.3065 m is used for the width of the drawing instead of Dugas' foot unit of 0.2985 m, there are no differences between the fitted circle and the graphical method.

The method is also very flexible. Reducing the number of dactyl subdivisions increases the amount of maximum entasis: for example, dividing the dactyl into five equal parts instead of eight would have increased the entasis from 11 mm to 17 mm (and at the same time the drawing is widened from eight to nine dactyls). With some test drawings the architect could quickly have discovered the desired combination of shaft profile and taper.

The only drawback with the method is that a division of a dactyl into small equal parts is necessary, but, in fact, there is no indication in literary sources or inscriptions that Greek builders ever used any fractions of a dactyl less than a half.[49] On the other hand, if small fractions of a dactyl were used, it is precisely for the entasis design that they would have been required.

The second alternative design method presented here is quite different from the method of drawing described above. The required space is much larger, ca. 4.5 × 1.5 m; the equipment required is a ruler and a long string for drawing the arc of the circle. Figure 28 presents a solution based on drawing a true circle. I will again discuss the drawing in terms of Dugas' foot unit. The centre of the circle is drawn one and a half times the height of the drawing, 45 dactyls, below the base line; the radius of the circle is half of the shaft height, or 15 feet. The right part of Figure 28 shows the drawing of the shaft profile at larger scale. The arc of the circle fits fairly accurately to the points of the first drawing method; these points are plotted as small circles in Figure 28. The amount of maximum entasis is 9 mm, slightly less than the determined entasis at Tegea of 11 mm. The architect could have increased the amount of entasis by bringing the centre of the circle slightly closer to the drawing area. The method is extremely simple, and, with a little testing, both the taper and entasis of the shaft can be controlled. Transforming the design to full scale, the realised shaft profile becomes an elliptical arc.

[47] The figures for *'Design drawing'* and *'Unit of* 0.3065 m' are calculated using the formula of n. 46 above. In the former d = 0.2985 m / 16, and in the latter d = 0.3065 m / 16.

[48] For the circle formula and the used estimated parameters, see Table 11.

[49] Coulton 1975, 92–93.

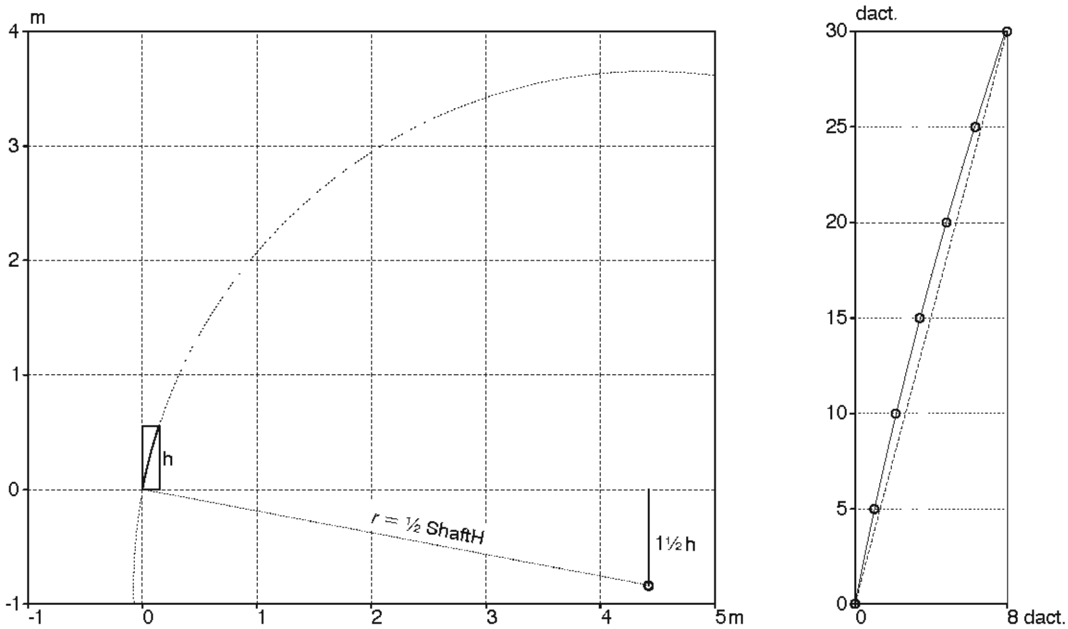

Figure 28. Hypothetical design drawing of the shaft profile (large circle).

In conclusion, both of the methods could easily have been employed by the ancient architect. I find the latter method slightly more attractive because of its simplicity; it also avoids the problem of using subdivisions of a dactyl. Therefore, I suggest that the shaft profile at Tegea was quite likely to have been designed using the circle method.

5. Column Proportions

With the column height and shaft profile of the temple of Athena Alea quite accurately determined it is possible compare the column proportions of different Doric buildings in the Peloponnese and Central Greece (Table 13). The slight modification in the column height at Tegea does not significantly alter the proportion $\frac{\text{column height}}{\text{lower diameter between the arrises}}$: there is a trend, even if it is not very clear, to make the column more slender during the fourth century. The columns of the two tholoi at Delphi and at Epidauros, and the treasury at Delphi are proportionally significantly taller than the columns of the other buildings (column *A*). [50]

On the other hand no chronological trends can be observed in the taper of column (column *B*) or the proportional flute depths (columns *C* and *D*). The

[50] The columns of the tholoi are probably more slender in order to balance their proportionally greater width; see Roux 1961, 321 and Tomlinson 1983, 64.

Table 13. Column proportions (late 5th – late 4th century BC).

	A.	*B.*	*C.*	*D.*	*E.*	*F.*
Bassai, t. of Apollo (not frontal)	5.359	3.88–3.91	0.205	0.168	–	–
Argive Heraion, second t. of Hera	5.4–5.7[51]	4.3–4.5	0.20	0.15	*exists*	
Delphi, tholos	6.83	3.53	0.206	0.138	0.09	0.53
Delphi, 4th cent. t. Apollo	5.44	3.69		0.226	*exists*	
Delphi, 4th cent. t. Athena	5.91	3.41	0.268	0.248	0.08	0.52
Epidauros, tholos (11/12 drums)	6.9 / 7.5	3.5 / 3.5	0.17	0.13	0.15 / 0.14	0.48–0.52
Tegea, t. of Athena Alea	6.16–6.18	3.79–3.80	0.19	0.16	0.12	0.48–0.53
Delphi, treasury of Kyrene	6.94	2.69			0.22	0.56
Nemea, t. of Zeus	6.342	3.33	0.216	0.152	0.14[52]	0.51[52]
Stratos, t. of Zeus	6.0?	4.2?	0.22	0.13		

A. Proportional height of the column = ColH / Diam_{LA}
B. Taper of column shaft (%) = 100 × (Diam_{LA} – Diam_{UA}) / ShaftH
C. Proportional flute depth at the bottom of the shaft = [(Diam_{LA} – Diam_{L}) / 2] / FlW_{L}
D. Proportional flute depth at the top of the shaft = [(Diam_{UA} – Diam_{U}) / 2] / FlW_{U}
E. Proportional emphasis of maximum entasis (%) = 100 × Ent_{max} / ShaftH
F. Proportional position of maximum entasis in the shaft = EntH / ShaftH

fluting is always more shallow at the top of the shaft than at the bottom. The proportional emphasis of the maximum entasis varies during the fourth century (column *E*), but it is always placed approximately in the middle of the shaft (column *F*). In the two earlier buildings at Delphi the entasis is less pronounced. The emphasised entasis of the treasury of Kyrene is most likely a feature of 'Kyrenaian' Doric order; the building is clearly different in other respects, as well, from mainland Doric style.[53]

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[51] Based on the preserved 14 column drums at the Heraion the bootstrap-*t* 95% confidence interval for the mean can be calculated as 0.825–0.865 m; the height of the column shaft cannot be determined any more accurately than as 6.60–6.92 m and the column height with the capital as 7.10–7.43 m (C. Pfaff's proposal of 7.32 m for the column height cannot be sustained); for the drum heights at the Heraion, see Pfaff 1992, 123, pls. 116–123.

[52] Calculated for the pronaos column.

[53] See Pakkanen 1997, 332–334.

VII. Conclusions

This study partially presents the results of the documentation project on the blocks of the fourth century BC temple of Athena Alea at Tegea obtained from 1993–1998; the building block documentation is directly connected with the five year Norwegian excavation project (1990–1994) in the sanctuary led by E. Østby.

The 49 column drums preserving their full height and both the lower and upper diameters were documented on zone sheets: each peristyle column of the temple had consisted of six drums and, correspondingly, the shaft was divided into six overlapping parts which take the entasis of the shaft into consideration. The measurements were recorded and the positions of the empolion cutting and the dowels drawn on the zone sheets. Once the documentation was complete it became possible to identify the blocks with the drums numbered by Ch. Dugas and M. Clemmensen and published in 1924. The previous measurements were discovered to be generally reliable.

The lower diameter of the bottom drums between the flutes is 1.45–1.46 m and between the arrises ca. 1.55 m. The corresponding measurements for the top of the shaft are 1.15–1.16 m and 1.20–1.21 m. The corner columns were not thickened. The peristyle columns were standing vertical: the height variation of the bottom drums is not enough to incline the columns towards the interior—as the previous reconstruction shows—but only to correct the horizontal curvature of the stylobate. All the drums used in the study can be shown to be from the peristyle order.

The variation of the capital dimensions, even though small, creates difficulties in the analysis of architectural proportions—individual capitals at Tegea could be placed on the basis of proportions almost anywhere in the chronological list of fourth century buildings. The Tegea capitals support the conclusions reached by J. J. Coulton in his study on Doric capitals (1979): 1) the homogeneity of the fourth century capitals is most likely a result of the use of proportional rules, and 2) the use of proportions to date buildings should be reconsidered.

The horizontal curvature of the foundations has been restudied: the central part of the south flank was measured to be 0.080 m higher than the south-east corner of the foundations, and the height difference on the west short side is 0.054 m. The entablature has been shown to have horizontal curvature as well. Nine of the twelve entablature blocks show signs of being adjusted for horizontal curvature: the range of the angle measurements is 89.7–90.8°.

The height of the column can be most reliably determined using computer-intensive statistics: the bootstrap-*t* method is able to deal with the non-random and non-normal drum height distribution. The validity of the method was confirmed by Monte Carlo simulation. Non-randomness of the data is shown to cause a conservative estimate of the shaft height, so the bootstrap-*t* method can be used to calculate the confidence interval of the shaft height. On the basis of matching pairs of drums the shaft height can be defined as 8.952–8.977 m at a confidence level of 95%; the column height with the capital is 9.544–9.580 m. This is 0.070–0.106 m higher than the previous reconstruction of 9.474 m, but perhaps even more significant than the definition of a new height is that millimetre exact reconstruction of the peristyle column at Tegea cannot be reached with the currently preserved material.

The number of possible drum combinations within the defined height range is 1,678. By determining which of the combinations produce an acceptable shaft profile within the measurement accuracy the amount of maximum entasis of is defined as 11 mm and the height of maximum projection as 48–53% of the shaft height.

It is demonstrated that all the foot units suggested by different scholars fit equally well to the column dimensions. Therefore, no decision can be made on the ancient foot unit used in the design of the temple on the basis of these measurements. Two alternative methods for designing the entasis curve are discussed; both are simple graphical methods which do not require any calculations. The second solution, based on a scale drawing and sketching a circle of approximately half the shaft height in radius, is proposed as the design method employed at Tegea.

The method for analysing the column height and shaft profile developed in this study can, with slight modifications, be applied elsewhere where there is enough architectural material preserved but the height of the building is not known. It is important to conduct the documentation so that individual margins can be determined for all the key measurements of the column drums—only data of this type can be used as input for the computer programs used in the analysis.

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ADelt	*Ἀρχαιολογικὸν Δελτίον*
AJA	*American Journal of Archaeology*
AM	*Mitteilungen des Deutschen Archäologischen Instituts, Athenische Abteilung*
BEFAR	Bibliothèque des Écoles françaises d'Athènes et de Rome
BCH	*Bulletin de correspondance hellénique*
BSA	*Annual of the British School at Athens*
CJS	*Canadian Journal of Statistics*
CRAI	*Comptes rendus. Académie des inscriptions & belles-lettres*
Délos	Exploration archéologique de Délos faite par l'École française d'Athènes
FdD	Fouilles de Delphes
Hesperia	*Hesperia. Journal of the American School of Classical Studies at Athens*
IstMitt	*Istanbuler Mitteilungen*
JAS	*Journal of Archaeological Science*
JdI	*Jahrbuch des Deutschen Archäologischen Instituts*
OpAth	*Opuscula Atheniensia*
Prakt	*Πρακτικὰ τῆς ἐν Ἀθήναις Ἀρχαιολογικῆς Ἑταιρείας*

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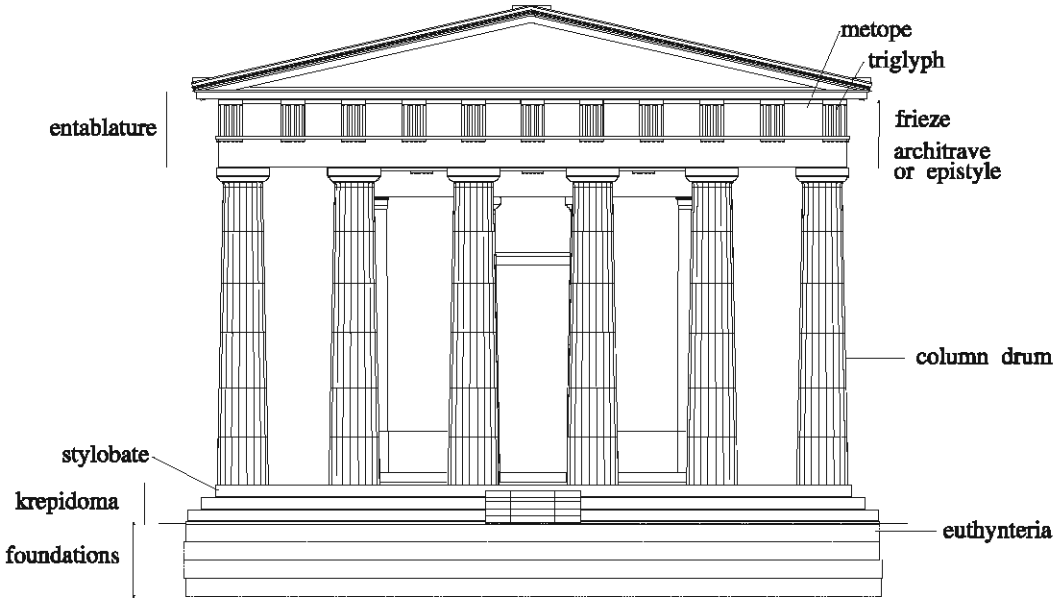

Fig. 29. Technical terms for building façade.

Glossary of Architectural Terms

abacus The flat slab forming the top part of the capital.

anathyrosis Smooth contact band at the edges of a block joined with another; the central part of the surface is roughly cut.

annulets The projecting rings between the neck (trachelion) and the echinus of the capital; see Fig. 12 on p. 33.

architrave Lintel block carried by columns, also called epistyle; see Fig. 29.

arris Sharp edge between two column flutes of a Doric column.

cella Central room of a temple.

column drum One course of a column shaft; see Fig. 29.

dowel Attachment used to secure blocks to the course below them; in Tegea the dowels are of iron with molten lead around them.

echinus Convex part of a Doric capital connecting the annulets and the abacus.

empolion Block at the centre of the column drum joint. Usually wooden, it consists of three parts: two which fit into the square cuttings of the adjoining drums, each with a round hole for the wooden centring pin.

entasis The slightly convex curve of the column taper.

entablature Superstructure of a building carried by columns; includes the architrave, frieze and cornice; see Fig. 29.

euthynteria Top course of foundations; see Fig. 29.

flute Vertical channel of a column shaft.

foundations Courses of blocks often needed to support e.g. krepidoma or cella wall; see Fig. 29.

frieze Central part of an entablature; see Fig. 29.

gutta Small cylindrical cuttings used in the Doric order under a regula and mutule.

krepidoma Platform of a temple, usually consisting of three steps; see Fig. 29.

metope Panels of a Doric frieze; see Fig. 29.

mutule Projecting slab at the bottom of a Doric cornice block.

opisthodomos Rear porch of a temple; cf. pronaos.

pronaos Front porch of a temple enclosed by side walls and by columns in front.

regula Rectangular strip under the taenia of a Doric architrave.

stylobate Top step of a krepidoma; see Fig. 29.

taenia Fascia at the top of a Doric architrave.

tholos Circular building.

triglyph Projecting member of a Doric frieze, between metopes and with two vertical grooves; see Fig. 29.

trachelion The neck of the capital; see Fig. 12 on p. 33.

Appendix A: Column drums

General abbreviations used in the appendix are listed on p. iii.
All measurements in meters unless otherwise stated.

Bl#	Block number
Dug#	Drum number in Dugas *et al.* 1924, app. II, 131–133
Pos	Position of the drum within the shaft

Table A1. Column drum diameter measurements (A2–3)

L	Lower diameter; measurement taken between flutes
U	Upper diameter; measurement taken between flutes
1A	Measurement taken between flutes 1A–10B
2A	Measurement taken between flutes 2A–9B
3A	Measurement taken between flutes 3A–8B
4A	Measurement taken between flutes 4A–7B
5A	Measurement taken between flutes 5A–6B
6A	Measurement taken between flutes 6A–5B
7A	Measurement taken between flutes 7A–4B
8A	Measurement taken between flutes 8A–3B
9A	Measurement taken between flutes 9A–2B
10A	Measurement taken between flutes 10A–1B

Table A2. Column drum height measurements (A4–5)

1A–10A, 10B–1B	Height of the drum measured along the bottom of the flute

Table A3. Column drums: measurement averages, margins, and differences (A6–8)

Av	Average of new measurements
Dugas	Measurement given in Dugas *et al.* 1924, app. II, 131–133
–	Negative margin of the new measurement
+	Positive margin of the new measurement
N	Number of new measurements taken of the drum
Differences	= Dugas – Av Printed in *italics* are the cases where the difference between Clemmensen's and the new column drum measurement (App. II, Dugas *et al.* 1924, 131–133 is larger than the error margin established on the basis of new measurements (see p. A8).

Catalogue of Column Drums and Drum Fragments (A9–42)

All photographs by J.P.

Schematic Drawings of Empolion and Dowel Holes (A43–59)

Scale 1:30 (original scale 1:25)

For drums in an upright position a north arrow is drawn next to the arris or flute facing north, and for drums lying on one side the top arris or flute is given an arrow pointing upwards.

Matching Drums (A60–61)

Table A1. Column drum diameter measurements.

Bl#	Dug#	Pos	L1A	L2A	L3A	L4A	L5A	L6A	L7A	L8A	L9A	L10A	L1A	U2A	U3A	U4A	U5A	U6A	U7A	U8A	U9A	U10A
3	D13	B	-	1.418	-	-	1.421	-	-	1.419	-	-	-	-	1.375	-	-	-	-	1.370	-	-
5	D15	D	-	-	1.330	-	1.331	-	-	-	-	-	-	-	1.269	-	1.270	-	1.269	-	1.270	-
6	D16	B	1.421	1.421	-	-	-	-	-	-	-	-	1.380	-	-	-	-	-	-	-	-	-
7	D17	D	-	-	1.322	-	-	-	-	1.325	-	1.322	-	-	-	-	-	-	-	1.267	-	-
8	D18	A	1.458	-	-	-	-	-	-	-	-	-	1.414	1.414	-	-	-	-	-	1.410	-	1.411
9	D19	C	-	-	-	-	-	-	-	-	1.375	-	1.323	1.322	1.322	-	-	-	-	-	-	-
15	D23	C	1.375	-	-	-	-	-	-	-	-	-	-	1.338	-	-	-	-	-	-	-	1.335
20	D27	E	-	-	-	-	-	-	-	-	-	1.264	-	-	-	-	-	1.211	-	1.213	-	-
21	D28	A	-	-	-	-	-	-	-	-	-	1.453	-	-	-	-	-	-	-	-	-	1.421
22	D29	F	1.214	-	-	-	-	-	-	-	-	-	-	-	-	1.150	-	-	1.151	-	-	-
24	D30	B	1.413	-	-	-	-	-	-	-	-	1.415	1.376	-	-	-	-	-	-	-	-	-
27	D01	C	1.375	1.378	-	-	-	-	-	-	-	1.377	-	-	-	-	-	-	-	-	-	-
33	D05	D	-	-	-	-	-	-	-	-	1.326	1.329	-	-	1.280	-	-	-	-	-	-	-
35	D06	D	-	1.326	-	-	-	-	-	-	-	-	-	1.268	-	-	-	-	1.268	-	1.268	1.270
36	D07	B	-	-	1.423	-	-	-	-	-	-	-	1.375	-	-	-	-	-	-	-	-	-
45	D08	B	1.419	-	1.417	-	1.417	-	1.418	-	1.417	-	-	-	-	-	1.370	-	-	-	-	-
46	D09	C	-	-	-	-	-	-	-	-	-	1.371	-	-	-	-	-	-	-	-	-	1.322
47	D10	A	-	-	-	-	-	-	-	1.457	-	1.460	1.419	-	-	-	1.421	1.421	1.420	1.421	1.416	1.420
48	D11	A	-	-	-	-	-	-	-	-	-	-	1.419	1.418	-	-	-	1.412	1.414	1.419	1.420	1.418
51	D72	A	1.458	-	-	-	-	-	-	-	-	-	1.422	1.422	1.422	1.422	1.421	1.420	1.422	1.421	1.422	1.421
77	D75	F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
79	D77	B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	D78	D	-	-	-	-	-	-	-	1.330	1.329	1.333	-	-	-	-	-	-	-	-	1.271	1.270
88	D80	E	1.279	-	1.279	-	-	-	-	-	-	-	1.213	1.218	-	-	-	-	-	-	-	-
89	D82	F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	D83	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
91	D84	B	1.423	-	-	-	-	-	-	-	-	-	1.377	-	-	-	-	-	-	-	-	-

B#	Dug#	Pos	L1A	L2A	L3A	L4A	L5A	L6A	L7A	L8A	L9A	L10A	U1A	U2A	U3A	U4A	U5A	U6A	U7A	U8A	U9A	U10A
92	D85	C	1.378	-	-	-	-	-	-	-	-	-	1.325	-	-	-	-	-	-	-	-	1.325
93	D86	A	-	-	-	-	-	-	-	-	-	-	1.426	-	-	-	-	-	-	-	-	-
94	D87	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.328
115	D33	E	1.273	-	-	-	-	-	-	-	1.270	-	1.210	-	-	-	-	-	-	-	-	1.210
135	D34	C	-	-	-	-	-	-	-	-	1.378	1.378	-	-	-	-	-	-	-	1.323	-	-
182	D31*	F	-	-	-	-	-	-	-	-	1.209	-	-	1.155	-	-	-	-	-	-	-	1.156
363	D37	C	-	-	-	-	-	-	1.375	-	-	-	1.338	-	-	-	-	-	-	-	1.337	-
395	D40	B	1.421	-	-	-	-	-	-	-	-	-	1.377	-	-	-	-	-	-	-	-	-
397	D41	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
401	D38	E	1.274	-	-	-	-	-	-	-	-	-	1.216	-	-	-	-	-	-	-	-	1.216
415	D44	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
454	D47	E	1.267	-	1.268	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.211	1.213
455	D46	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.267	-	-	-	-
492	D51	D	-	-	-	-	-	-	-	-	-	-	1.268	-	-	-	-	-	-	-	-	1.268
497	-	E	1.268	-	-	-	-	-	-	-	-	-	1.218	-	-	-	-	-	-	-	-	-
498	-	B	1.420	-	-	-	-	-	-	-	-	-	1.370	-	-	-	-	-	-	-	-	-
506	-	C	1.379	-	-	-	1.378	-	-	-	-	-	1.329	1.328	-	-	-	-	-	-	-	-
507	D53	F	-	-	-	-	-	-	-	-	-	1.206	-	-	-	-	-	-	-	-	-	1.155
529	-	B	-	-	-	-	-	-	-	-	-	1.418	-	-	-	-	-	-	-	-	-	1.376
533	-	E	1.274	-	-	-	-	-	-	-	-	-	1.223	-	-	-	-	-	-	-	1.223	-
542	D65	F	1.220	-	-	-	-	-	-	-	-	-	1.154	-	-	-	-	-	-	-	-	-
544	D66	F	1.215	-	-	-	-	-	-	-	-	-	1.158	-	-	-	-	-	-	-	-	-
561	-	B	1.417	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.374
563	D70	B	1.418	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.377
564	D71	A	-	-	-	-	-	-	-	-	-	1.455	-	-	-	-	-	-	-	-	-	1.416
809	-	C	-	-	-	-	-	-	-	-	-	1.365	-	-	-	-	-	-	-	-	-	1.332

Table A2. Column drum height measurements.

BI#	Dug#	Pos	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	10B	9B	8B	7B	6B	5B	4B	3B	2B	1B
3	D13	B	1.464	1.464	1.466	1.466	1.465	1.464	-	1.464	-	1.463	1.463	1.463	1.463	-	-	-	-	-	-	-
5	D15	D	1.659	-	-	-	-	-	-	-	-	-	-	-	1.655	1.657	1.658	1.658	1.660	1.657	1.658	1.659
6	D16	B	-	1.470	-	-	1.473	-	1.473	-	1.473	-	-	-	-	-	-	-	-	-	-	1.471
7	D17	D	-	-	1.514	-	-	1.516	-	1.516	-	1.514	-	1.514	-	1.513	-	1.512	-	1.513	-	1.515
8	D18	A	1.474	1.466	1.466	1.463	1.460	1.455	1.458	1.462	1.457	1.456	1.462	1.458	-	-	-	-	-	1.470	1.473	1.473
9	D19	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.666	1.669	-	-
15	D23	C	1.390	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	D27	E	-	-	-	-	-	1.387	1.385	-	-	-	-	-	-	-	-	1.373	-	-	-	-
21	D28	A	1.472	1.473	1.472	-	1.472	1.468	1.467	1.463	1.464	-	-	-	-	-	-	-	-	-	-	1.470
22	D29	F	1.318	-	-	-	-	-	1.323	-	-	-	-	-	1.319	1.319	1.321	1.319	1.318	1.319	1.320	1.319
24	D30	B	1.482	1.479	-	-	1.482	-	-	1.485	1.482	1.477	-	-	-	-	-	-	-	-	-	-
27	D01	C	-	-	-	-	-	-	1.441	1.444	-	1.444	1.445	-	-	-	-	-	-	-	-	-
33	D05	D	-	-	-	-	-	-	-	-	-	-	-	1.480	1.478	1.480	1.481	1.480	1.481	1.480	1.480	-
35	D06	D	-	1.494	-	-	-	-	-	-	-	-	-	1.493	1.493	-	1.492	-	1.493	-	-	-
36	D07	B	-	-	-	-	-	-	-	-	-	-	-	-	1.476	-	-	-	-	-	-	-
45	D08	B	-	-	-	-	-	-	-	-	-	-	-	1.478	1.478	-	-	-	-	-	-	-
46	D09	C	-	-	-	-	-	-	1.477	-	-	-	-	-	-	-	-	-	-	-	1.479	1.480
47	D10	A	1.475	-	1.473	1.471	1.472	1.472	1.471	1.469	1.470	1.470	1.469	-	-	-	-	-	-	-	1.473	1.475
48	D11	A	1.475	1.478	1.477	1.477	1.475	1.476	1.476	1.473	1.475	1.472	1.473	1.469	-	-	-	1.469	1.468	1.468	1.469	1.471
51	D72	A	1.473	-	-	-	-	-	-	-	-	-	1.472	1.474	1.474	1.474	1.475	1.476	1.475	1.474	1.474	1.474
77	D75	F	-	-	-	-	-	-	-	-	-	1.631	-	-	-	-	-	-	-	-	-	-
79	D77	B	-	1.482	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	D78	D	-	-	-	-	-	-	-	-	-	-	-	1.708	-	1.707	1.707	1.708	1.708	-	1.708	-
88	D80	E	1.661	1.661	-	1.660	1.660	-	-	-	1.663	-	1.663	1.663	-	-	-	-	-	-	-	-
89	D82	F	-	-	-	-	-	-	-	-	-	-	1.332	-	1.331	1.330	-	-	-	-	-	-
90	D83	D	-	-	-	-	-	-	1.415	-	-	-	-	-	-	-	-	-	-	-	-	-
91	D84	B	-	-	-	-	-	-	-	-	-	-	-	-	-	1.470	-	1.468	-	-	-	-

BH#	Dug#	Pos	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	10B	9B	8B	7B	6B	5B	4B	3B	2B	1B
92	D85	C	1.643	-	-	-	-	-	-	-	-	-	1.643	1.643	-	1.643	-	1.643	-	1.643	-	1.643
93	D86	A	-	-	-	-	-	-	-	-	-	-	-	-	-	1.468	1.466	1.467	1.464	-	-	-
94	D87	C	-	-	-	-	-	-	-	-	-	-	-	-	-	1.413	-	1.412	-	-	-	-
115	D33	E	-	-	1.579	-	1.580	-	-	-	1.577	-	-	-	-	-	-	-	-	-	-	-
135	D34	C	-	-	-	-	-	-	-	-	-	-	-	1.498	-	1.498	-	-	-	-	-	-
182	D31*	F	-	1.479	-	1.479	-	1.479	-	1.479	-	1.479	-	-	-	-	-	-	-	-	-	1.477
363	D37	C	-	-	-	-	-	-	-	-	-	-	-	-	-	1.319	-	-	1.322	-	-	-
395	D40	B	-	-	-	-	-	-	-	-	-	-	-	-	1.474	-	1.474	-	-	-	-	-
397	D41	C	-	-	-	-	-	1.561	-	-	-	-	-	-	-	-	-	-	-	-	-	-
401	D38	E	-	-	-	-	1.408	-	-	-	-	-	1.411	-	-	-	-	-	-	-	-	-
415	D44	D	-	-	-	-	1.447	1.447	-	-	-	-	-	-	-	-	-	-	-	-	-	-
454	D47	E	-	-	-	1.368	-	1.368	-	-	1.368	-	-	-	-	-	-	-	-	-	-	-
455	D46	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
492	D51	D	-	-	-	-	-	-	-	-	-	-	-	-	-	1.448	-	-	-	1.448	-	-
497	-	E	-	-	-	1.347	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
498	-	B	-	-	-	-	-	-	-	-	-	-	-	-	1.484	-	-	1.483	-	-	-	-
506	-	C	-	-	-	-	-	-	-	-	-	-	1.509	-	1.507	-	-	-	-	1.511	1.511	1.511
507	D53	F	1.349	1.349	1.350	1.349	1.347	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
529	-	B	-	-	-	-	-	-	-	-	-	-	-	1.472	-	-	-	1.473	-	-	-	-
533	-	E	1.356	-	-	-	-	-	-	-	-	-	-	-	-	1.356	-	-	-	-	-	-
542	D65	F	-	-	-	-	-	-	-	-	-	-	1.504	-	-	-	-	1.498	1.497	-	-	-
544	D66	F	1.487	1.485	-	-	-	-	-	-	-	-	-	-	1.480	-	-	-	-	-	1.483	-
561	-	B	-	-	1.472	1.472	-	-	1.476	-	1.477	1.477	-	-	-	-	-	-	-	-	-	-
563	D70	B	1.477	-	-	-	-	-	-	1.479	-	-	-	-	-	-	-	-	-	-	-	-
564	D71	A	-	-	-	-	-	-	-	-	-	-	-	1.471	-	1.470	-	1.472	-	1.473	-	1.472
809	-	C	-	1.457	-	1.456	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-