The Water Clock in the Tower of the Winds

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PLATES 111-118

Paradoxically, the Tower of the Winds in the Roman Agora of Athens has been the subject of few studies, although it is one of the very small number of buildings from antiquity that still stands virtually intact, never buried, and in continuous occupation till recent times (pl. 111, figs. 1, 2). James Stuart and Nicholas Revett[1] published their celebrated account, based on precise measurements, in 1762, and identified the tower as a combination of wind-vane, sundials and water clock. They remarked about the water clock: "No Attempt will be made at present, to retrieve the particular Structure of this Machine; or to show precisely, the Manner in which the Traces now remaining, were connected with the Parts that have been long since destroyed," (pl. 112, figs. 3, 4, 5). Henry S. Robinson,[2] in the only extensive recent report on the building, added much to our knowledge of the dating and the structure, but in commenting on the remaining traces of the internal workings he had to note: "How these elements served in the operation of the *Horologion*, it is impossible to state, since the mechanism of the clock has long since disappeared."

The present study attempts to fill this long-standing lacuna. A careful examination of both the archaeological evidence[3] and the ancient sources on water clocks[4] has enabled us to present a practical restoration of the mechanism designed by Andronikos of Kyrrhos in Macedonia, probably near the beginning of the second half of the first century B.C.

The Tower of the Winds is basically an octagonal marble structure, 25′ 8″ in diameter and 47′ in height to the top of the roof finial. Small porches shelter doorways on two sides, and a small cylindrical tower is attached to the back or south side. On each of the eight sides is a sundial, and on the curved surface of the cylindrical tower there is a ninth (pl. 113, figs. 10, 11, and see appendix).

[1] J. Stuart and N. Revett, *The Antiquities of Athens* I (London 1762) chap. III, pp. 13-25, pls. I-XIX.

[2] Henry S. Robinson, "The Tower of Winds and the Roman Market-Place," *AJA* 47 (1943) 291-305. He dates the structure between 100 and 37 B.C. We lean heavily on this paper and refer the reader to it for general treatment of classical and archaeological problems.

[3] The field investigation at the Tower of Winds was carried out by us over several years. Our thanks are due to Alison Frantz who in 1962 made the photographs illustrating this report. In 1963 we were assisted by Andrew Oliver Jr. of The Metropolitan Museum of Art, and the final survey was made by one of us (D.P.) during September 1964, with the assistance of David Beal as photographer and George Stuart as architectural draughtsman. In 1966 Robert C. Magis visited Athens and drew the reconstruction of the water clock. We should like to express our grateful appreciation to the Exploration Fund of the National Geographic Society of Washington, D.C. which made possible such assistance. (A preliminary report on our investigations appeared in the *National Geographic Magazine*, April 1967, pp. 586-596, "The Tower of the Winds," by Derek J. de Solla Price.) We also must record our gratitude to the Archaeological Service of the Greek Government, and in particular to N. Platon, Ephor of Antiquities in Athens, for his support and help in giving permission for this work to be undertaken. Generous aid and most sage advice and criticism was also given by Prof. Homer A. Thompson, Director of the Agora Excavations, and Prof. Henry S. Robinson, Director of the American School of Classical Studies in Athens. Workmen and some equipment from the Agora excavations were generously made available to us on the site. For the investigation of the dial on Tenos we wish to thank the authorities of the Museum there, and for further complete cooperation, we were once more indebted to the late Dr. Christos Karouzos, Director of the National Archaeological Museum in Athens, for continued study of the fragments of the Antikythera Mechanism. For special help with the reconstruction of the Salzburg Anaphoric Clock fragment we thank Mr. L. C. Eichner of Clifton, N.J.

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[4] All classical texts relevant to water clocks have been published and commented upon by Max C. P. Schmidt, *Kulturhistorische Beiträge zur Kenntnis des Griechischen und Römischen Altertums, Zweites Heft; Die Entstehung der Antiken Wasseruhr* (Leipzig 1912). The technical commentary in this study is now much out of date; in the present work we have followed in most places the positions and interpretations taken by A. G. Drachmann in his books: *Ktesibios, Philon and Heron, A Study in Ancient Pneumatics* (Copenhagen 1948) and *The Mechanical Technology of Greek and Roman Antiquity* (Copenhagen, Madison and London, 1963). For present views on the cultural significance of this line of ancient clocks, see Derek J. de Solla Price, *Science since Babylon* (New Haven 1962) Ch. 2.

At the outset it must be admitted that literary and historical allusions to the Tower of the Winds or its designer give almost no indication that the building was anything more than an elaborate wind-vane. It is mentioned only by Vitruvius (26-14 B.C.)[5] and by Varro (before 37 B.C.).[6] Neither of these authors mentions the sundials, or anything in the interior; this is particularly perplexing in the case of Vitruvius who devotes considerable space in his books to the discussion of both sundials and water clocks, giving many details of construction as well as the names of notable innovators. He refers to the structure only as an "octagonal marble tower," and mentions that the roof was surmounted by a wind-vane in the form of a bronze Triton which turned and pointed to the sculptured images of the eight winds (pls. 114-115, figs. 6-9). Varro calls it the *horologium*, a term which may apply equally to sundials and water clock, but hardly to a simple wind-vane.

The ancient name of the stream and the fountain furnishing the stream which is led to the Tower of the Winds is the Clepsydra, a term also used for a water clock, as was noted by Stuart and Revett. Aristophanes refers to the fountain (*Lysistrata* v. 909) as being near the Grotto of Pan, and in Turkish times it was noted the stream still passed within ten feet of the Tower. The name clepsydra (literally "water thief," a term first applied to a kind of wine drawer, rather like a modern chemical pipette, rather than to all types of water clock), was used for the stream as early as Aristophanes, long before the Tower of the Winds was built. Therefore the reference must be to some much earlier structure if, indeed, it is to be taken in this sense. In the ancient Agora there is a sequence of such clepsydra housings,[7] although none of them is perhaps quite so old as the time of Aristophanes (b. 444 B.C.).

One can, of course, hardly admit an *argumentum ex silentio* involving the lack of a description on the part of Vitruvius and all other authors of the period whose works have come down to us. This is a field in which ancient literature is curiously meager, as we well know from the complete lack of any literary reference to a technology that could produce the Antikythera Mechanism[8] of the same date. The same argument applies to the sundials. There is nothing whatsoever to indicate that they may have been a later embellishment of the building as some have suggested. On the contrary, the fact that the equinoctial lines on the north and south dials run precisely, across the width of the wall from the first hour line to the eleventh, is an indication that their scale was conceived with the same geometrical economy and neatness that characterizes the plan of the rest of the building. We suggest only that the dial lines, and perhaps the wind names too, were originally filled with paint of a dark color[9] which was later washed away by wind and rain. At present the markings are scarcely visible from ground level; they certainly do not stand out in a way consistent with their place and skill of execution. Possibly the fading of the lines and the removal of the valuable bronze of the gnomons[10] helped leave unmentioned this function of the Tower. Similarly, early removal of valuable parts of the internal mechanism might have obliterated memory of the water clock.

It is to the evidence supplied by preserved traces in the building itself that we must turn for a discussion of the water clock mechanism (pl. 116, fig. 13). In only three places is the foundation pierced by apertures through which water could have been led in or out of the structure (pl. 117, figs. 14, 15). At the center of the octagonal tower there is a large circular hole carefully cut in the massive central block; this hole descends through the foundation. We could find no trace of a tunnel that Stuart and Revett indicated as proceeding in a southwesterly

[5] Vitruvius 1.6.4.

[6] Varro, *RR.* 3.5.17.

[7] Private communication, Homer A. Thompson. The best example of such a water clock structure is not in the Agora but at Oropous, *ArchEph* (1918) 111-113.

[8] Derek J. de Solla Price, "An Ancient Greek Computer," *Scientific American* (June 1959) 60-67.

[9] Such black paint is still visible on the lines of the massive conical skaphe dial that overhangs the cliff of the Acropolis above the Theater of Dionysius. It is probably not a recent restoration, for the gnomon is missing and seems never to have been replaced, and without that the markings would be useless. The dials on the Tower of the Winds were repainted and Roman numerals added during the late 19th century; see Franz M. Feldhaus, *Die Technik der Antike und des Mittelaltere* (Potsdam 1931) 147, fig. 181, and Mrs. Alfred Gatty, *The Book of Sundials* (London 1900) 39. There is no trace of such paint now, but the former presence of these numerals may have given rise to the persistent rumor that the dials were a later addition to the Tower, see n. 32.

[10] Only about 1 per cent of all ancient dials are intact with their gnomons. An ancient bronze gnomon was shaped like an elongated triangular or square pyramid with a short T-piece at the base. The T was inserted into a rectangular cavity in the stone, and keyed in place with molten lead. Presumably the original gnomons of the Tower were of this square pyramidal form. There is no authority for the restored form of a round stick bearing a ball on the tip, installed in 1845.

direction from this hole, but feel there might well have been an enclosed earthenware drain leading in some general westerly direction below the level of the foundation. Slightly south of the center of the cylindrical tower there is a large and somewhat irregular square hole which descends through three courses and may well link up with a channel beneath the foundation. Lastly, just right of center as one looks at the back wall of the cylindrical tower, there is a small and slightly irregular circular hole cut through the floor block at the base of the wall. Being so small and so near the wall, it could not be plumbed to any great depth. Cut in the wall directly above this hole is a semicircular channel running vertically to the uppermost preserved course. At intervals there are pairs of holes (one on each side of the cut) which very likely once held clamps supporting a partially recessed pipe coming through the base hole and running up the wall of the tower. Since the cut is rather wider at the bottom than at the top, it leads one to surmise that this must have been for the inflow pipe, wide at the mouth and becoming more constricted in its later path.

We identify the small round hole as the inlet for water, and the two larger openings as outlet drains. Presumably the water came in under high pressure in a lead pipe fed by the Clepsydra spring, high up the slope of the Acropolis and well above the level of the roof of the Tower of the Winds.[11] It went out through the two drains, probably connected at some point below foundation level, and led down the slope of the Agora, perhaps to the drains which served the ancient public lavatory situated down the slope from the Tower near the entrance to the site.

Surrounding the central circular drain hole in the floor of the octagonal tower there is a shallow ring-shaped depression about three feet in diameter. This ring has six approximately radial grooves in it, each groove ending in a small circular depression at the perimeter of the ring. A channel which runs from the cylindrical tower to this central hole crosses the depressed area where a seventh groove could have been located. Although the seven radii are not equally spaced apart, it is quite clear that the intention was to make seven and not eight, the number which might have been expected in an octagonal structure.[12]

Around the central area, at some distance from it, there is a set of eight curved grooves and three pillar-sockets arranged in a circle with an inner diameter equal to the internal width of any of the octagonal walls of the Tower. The eight grooves are of equal length; six lie together, the other two are set between the three pillar sockets. Each groove subtends about 36°, and each pillar about 24°. On the east side an additional groove runs parallel to and within the first, apparently the result of a miscalculation by the mason. The error was, in fact, not discovered before a second groove had been started on the northeast side, but this one seems to have been abandoned after only an inch or two. The mistake could have been concealed by overlying stone when the structure was complete.

The circular grooves were the base for a marble balustrade or railing surrounding the elements now missing from the center of the building; the railing was presumably designed to protect the central mechanism from the curiosity of spectators. Lying about in the Tower are several pieces of this balustrade, with tongues which exactly fit the grooves. The source of these fragments is not known, but we were able to find several more pieces, some of them quite large, lying on stone piles near the Tower and elsewhere in the Roman Agora; almost certainly, beneath the surfaces of the stored piles, there are many more such fragments which we hope will one day be identified and put in place with the others within the Tower. From the recovered fragments we have been able to restore the form of the railing's lattice structure, base, handrail, and two patterns of side decoration, as well as the method by which adjoining sections were fitted together (pl. 116, fig. 16). Unfortunately, in the absence of any complete join of a vertical section, we know only the length of each section, not the height. Presumably the balustrade was near elbow-height. Less certain is the arrangement of

[11] According to the *Hachette Guide to Greece* (1955) 135, "the source of the water supply to the Tower is 54 yards 2 feet above the level of the (base of?) the Tower." In the engraving of the general scene given by Stuart and Revett (pl. 1), the line of the water pipe in Turkish times shows up as a horizontal band of vegetation running along the adjoining wall to the right of the Tower.

[12] The seven grooves are faithfully shown in the ground plan of Stuart and Revett, but they do not seem to have been remarked upon or reproduced by other commentators. Robinson's sketch plan shows the ring as grooveless, and the balustrade grooves as a continuous band interrupted only by the three pillars.

the two types of side decoration in the lattice. We suggest provisionally that the type with the double vertical line (A) was used at places where sections of balustrade met, and that with a single line (B) in places where a section of balustrade abutted one of the three pillars.

A channel of roughly semicircular profile runs in an irregular line from the square drain hole in the cylindrical tower past the east side of the central pillar of the three in the balustrade circle, and thence to the central drain hole. Just within the balustrade circle the channel divides into three branches: two channels lead to the two flanking pillar-sockets of the circle, and the third runs to the round central drain hole. The incline of the main channel is negligible, and water poured into the middle of the channel flows both ways to the two drains. At the middle of the long stretch of the channel is a slight widening, and at the end of the eastern fork, near the pillar, we found heavy traces of a water stain. It seems irrefutable that the channel was made to accommodate a water pipe, leading from the cylindrical tower to the center structure and the two flanking pillars. The channel might also have supplied the middle pillar, but the stone is broken at the point where a channel might have been, and we cannot be sure about it. The enlargement in the channel might well be for a join in the main pipe. The water stain, only evident around the eastern pillar and presumably due to a loose fitting in that region, proved on chemical analysis of some chippings[13] to contain only iron with insignificant traces of copper and lead. We must presume that the stain comes from iron pins and fixtures in the structure rather than from the presumed lead of the piping. The casual layout and the irregularity of the cut of the channels indicate that this part of the construction was not a matter for drawing-board geometrical design. Conceivably it was the work of some engineering artisan, rather than of Andronikos himself.

The floor also contains an inner and an outer set of shallow holes, each set forming an octagon. These holes are far too shallow to have kept a post upright without further support. Robinson noted, in the outer set, that a hole is lacking only at the center of the NE doorway, and he remarked that, whatever the function of these holes, the absence of this one hole is an indication that only the NE doorway was in use when the holes functioned; with his conclusion we concur. We feel it unlikely that one doorway should have been blocked in the original design, and this leads us to suggest that the two sets of holes may have been provided for locating pins of sections of a removable wooden floor. Such a floor might well have been useful for providing a dry walk in the midst of gushing water, and its presence might account for the otherwise curious fact that at present one has to step quite far down from the entrance doors to the level of the stone floor. On the other hand, and more likely, the floor may have been added when the Tower was denuded of its interior fixtures and converted to a Christian church in late Roman times.[14]

Connecting the cylindrical tower and the octagonal building there is an irregular aperture, or small doorway, at floor level. To the left of it is preserved part of the outline of an ornamental frame carved in the marble, but no trace of such a frame exists to the right (pl. 116, fig. 17). One block is missing above this frame, and three blocks surrounding the original opening have been broken or chipped away to enlarge the doorway for more convenient access—presumably at an early date before the floor level was raised. If one assumes symmetry and supposes that the ornamental frame went as far to the right as possible on the missing portions, then the original aperture would have been two feet square and exactly centered over the pipe groove in the floor; the join of the two upper blocks is also directly above the center of this aperture. Presumably when the structure was intact the aperture would have normally been closed by a door of some sort, but no traces of any hinge or socket holes exist. It will be noted that the missing block was supported originally on the right only by a small portion of the block below it. When this block fell, breaking some of the stone of the block below, the aperture was apparently

[13] We thank Prof. Kenneth G. Wiberg of the Yale University Chemical Department for undertaking this analysis.

[14] An inscribed cross in the interior of the east wall must date from this period; it proves by its height that ground level was still in keeping with the original design. At a later date ground level both inside and outside the Tower was raised to the height of the lower cornice so that one could enter only by stooping. The preserved *Mihrab* at the SSE corner of the interior of the Tower, in the direction of Mecca, has its base on this cornice, showing that the fill had occurred between the Tower's first use as a church and its later use as a *Teckeh* (*Tekke*) for the Islamic cult of whirling dervishes.

further enlarged artificially, perhaps at the time when the structure was in use as a church.

For completeness we should remark that there is no trace on the lower cornice of any beam work that could have been used to divide the tower into two rooms by means of a wooden ceiling. Furthermore there is no hole running right through the original marble finial which surmounts the roof,[15] (pl. 117, fig. 12), exactly as shown by Stuart and Revett. We therefore come to the conclusion that the considerable height of the tower was occasioned purely by a desire to place the wind-vane and the sundials at a good altitude,[16] and that the vane did not connect with any internal indicator. Moreover, in the absence of an upper room, any concealed mechanism could only be in the cylindrical tower. Finally, it should be mentioned also that the lower walls and cornice of the octagonal tower carry no inscription and bear no traces of engraved or inscribed tablets that might have been fixed to them. There is, therefore, no room for the conjecture we might otherwise have made, that the six walls not occupied by doorways each could have been provided with an inscription showing two months of a *parapegma* type of calendar such as that of Geminos, giving the expected astronomical and meteorological phenomena on a day-by-day basis. Similarly one must now discount the conjecture of Inwood[17] that there may have been a sculptured band to indicate the hours resting on the lower interior cornice of the building. Nor could wind direction be shown by means of a pointer connected in some way to the external bronze Triton wind-vane, even though Varro indicates that he had such a device in his version of a weathervane on a garden house.

The cylindrical tower is divided into an upper and lower chamber by a stone shelf at the level of the lower cornice of the building; there is only a tiny crawl space between.[18] It follows, therefore, that the upper chamber must have been most difficult of access, and that any large object inside must have been put in place before the tower was roofed. We have suggested above that the pipe carrying water to the Tower of the Winds led to this upper chamber, and we further suggest that this chamber once contained a large reservoir or water tank. The entire upper chamber may well have been lined with waterproof cement and used as a tank.

From the assembled evidence the least one could assume would be a series of fountains within the octagonal tower, but for this it would seem unnecessary to pipe the water to the upper chamber of the cylindrical tower and then lower it, using the lower chamber for nothing but the pipe leading to the floor channel. Even if it were sensible to suppose that this was done to provide a settling tank to take dirt out of the water (which is unpleasantly brackish), it still offers no explanation for the square drain on the floor of the cylindrical tower. To explain this one would have to assume that water from the upper tank was piped into some lower tank which had an outflow taken care of by this drain, as well as a piped outflow which led along the floor channels to the central structure in the octagonal tower.

Such a strange device is not listed in the hydraulic arrangements well documented by Frontinus,[19] nor duplicated in the preserved fountains. It is, however, most fortunately, very similar to the arrangement of one of the most common varieties of water clock, known to Ktesibios (ca. 300-230 B.C.), Philon (ca. 250-200 B.C.) and Heron (ca. A.D. 60), reported in some detail by Vitruvius, and very competently analyzed in recent times by Drachmann.[20] Basically, there are two types of

[15] Alice Morse Earle, *Sundials and Roses of Yesterday* (New York 1902) 57. It should perhaps be noted that this photograph shows the Turkish plaster turban surmounting the roof; this was removed by Orlandos in 1919, and the original marble finial which had been lying on the ground was replaced. At the same time terracotta tiles were placed over the leaking joints of the marble roofing slabs. The plaster turban may also be seen in the general view (pl. 1) given by Stuart and Revett.

[16] In spite of the altitude, it has frequently been remarked that no wind-vane, set as this was in the shadow of the Acropolis, could be unaffected by that shelter. The vane must have given rather false indications of all winds from a generally southerly direction.

[17] H. W. Inwood, *The Erechtheion at Athens . . .* (London 1827) 122-123 and pl. XIX. A marble sculptured frieze is illustrated in his reconstruction. "As a figure turned, and with a wand pointed to the band of sculpture round the exterior, representing the winds, perhaps some emblematical figure elevated itself from the pavement, and was turned by the water dial within, pointing to a somewhat similar band of sculpture, representing the hours of the day in the interior."

[18] An approximate sketch of this arrangement is shown from Graef in Baumeister, *Denkmäler des klassischen Altertums*, fig. 2369, p. 2114. It should be noted that the interior of the cylindrical tower, previously blocked by the masonry shelf which has now been replaced and strengthened, was not excavated by Stuart and Revett, and was not described by them.

[19] Ed. Clemens Herschel, *Frontinus and the Water Supply of the City of Rome* (Boston 1899).

[20] A. G. Drachmann, *Ktesibios, Philon and Heron, A Study in Ancient Pneumatics* (Copenhagen 1948).

water clock, the outflow clepsydra and the inflow clepsydra. The outflow clepsydra was known as early as the third millennium B.C. in Egypt,[21] and an example from the Athenian law courts was excavated from a well in the old Agora.[22] In this type water is allowed to escape from a vessel by dripping from an orifice near its base. Time is then calculated by measuring the fall of the water level, or the entire period taken for all the water to drain away. The disadvantage of this type of clepsydra is that the rate of flow through the orifice depends on the head of water above it; therefore as the water drains away the flow becomes slower. This could be partially compensated for by making the vessel in the flower-pot shape of the Egyptian tradition, but for all purposes except the law court, where it indicated a fixed time interval, this type was soon superseded by the inflow clepsydra.

In the inflow device, the invention of which Vitruvius ascribes to Ktesibios, water was fed into a tank somehow equipped to provide a constant head of water. From a small orifice near the bottom of the tank, water dripped at a constant rate into a cylindrical container provided with a float; the float indicated the change in water level and therefore the time elapsed. When the cylinder was filled, the clock had to be "rewound" by emptying it; the float sank to the bottom,[23] to be gradually raised again by the constant drip of water from the tank above. The cylindrical tower section of the Tower of the Winds is perfectly suited to house such an apparatus: the upper chamber to hold the constant head tank, the lower chamber the cylinder with its float, and the drain to take care of periodic (probably daily) emptying or "rewinding."

To provide the constant head of water in the tank in the upper chamber there are two possible methods, very different in effect. In the parastatic clock ascribed to Ktesibios a device was used, somewhat similar to a modern lavatory cistern, in which a float worked a faucet which cut off the supply of inflowing water as soon as a predetermined level was reached.[24] In its simplest form, this device would consist of a floating ball which could block an inverted funnel-shaped enlargement at the end of the inflow pipe. This has the advantage of not wasting water, but any faults in construction or material would soon become so aggravated by corrosion and deposits from the water that the mechanism would need constant cleaning and attention. Such problems would be particularly acute when dealing with an inflow supply under high pressure, as at the Tower of the Winds. The second method, however, is completely trouble-free and independent of water pressure; therefore we feel certain that this was the method used in the Tower of the Winds. The upper tank is provided, near the top, with an overflow pipe to carry away surplus water, leaving the container constantly full to this level; water dripped into the lower container through a pipe connected to the bottom of the upper reservoir.

To maintain this constant head of water, some water must necessarily be wasted. We feel, however, that in the case of the Tower of the Winds the waste was turned to good use by leading the excess water from the overflow pipe down the lower chamber, along the channels in the floor, to the two pillars and central structure. There it could have supplied decorative fountains or perhaps animated singing birds and other automated *parerga* in the Heronic tradition.

It is unlikely that the water clock lower container was in the center of the octagonal structure: it could not have been set inside the central hole since the drain tap at the bottom would have been inaccessible. If it were above ground level all the art would have been lost unless the works were hidden in a large structure.

Now let us summarize the reconstruction of the hydraulic mechanism of the lost water clock (pl. 118, fig. 18). Water from the Clepsydra Spring, located on the north slope of the Acropolis near the Grotto of Pan, entered the cylindrical tower under hydraulic pressure. The pipe through which it entered ran up the wall and emptied into a large up-

21 Ludwig Borchardt, *Die Geschichte der Zeitmessung und der Uhren, herausgegeben von Ernst von Bassermann-Jordan, Band I, Lieferung B. Altägyptische Zeitmessung von Ludwig Borchardt* (Berlin and Leipzig 1920).

22 Suzanne Young, "An Athenian Clepsydra," *Hesperia* 8 (1939) 274-284.

23 It is worth remarking that during such a rewinding the spectator would see the internal showpiece or dial rapidly retracing its entire diurnal rotation from the previous day. It has been suggested by Brumbaugh, *Studium Generale* 14-(9) (1961) pp. 520-527, that such a rewinding might well account for the Myth of Cosmic Reversal in Plato's *Statesman*.

24 Such a mechanism is described in the so-called "Clock of Archimedes," but Drachmann (1948) 36-41, shows that this feature is post-Heronic and probably Muslim. Certainly the float controller is common in the tradition of al-Jazari and other later makers of monumental water clocks.

per reservoir, which supplied water under constant pressure to the water clock. An overflow drain was located near the top of the tank, from which the water, of varying rate of flow, was piped to the center of the octagonal tower to operate fountains or other displays. Water for the clock was drawn off near the bottom of the tank and was controlled by a carefully regulated valve. It was adjusted so that a lower tank would be completely filled in precisely 24 hours. As the lower tank filled, a float rose with the water, and a thin bronze chain connected to the float transmitted its motion to a display apparatus in the center of the octagonal tower. At the end of 24 hours, when the lower tank was filled and the float had reached its top position, an attendant opened the valve at the bottom of this tank and allowed the water to drain into the rectangular drain hole. The process was then repeated for the next 24 hours. The water supply for the clock was drawn off a little above the bottom of the supply tank, so that any sludge or dirt which had settled to the bottom of the tank would not clog the fine orifice used to regulate the water clock. The arrangement described here is in accord with comparable mechanisms described by Vitruvius.

Although we can be reasonably certain about the clock mechanism itself, we cannot be definitive about the visual device used to display the information transmitted by the clock mechanism—there is a variety of possibilities. For example, the chain connected to the float could turn a gear which would cause a calibrated rod to rise and indicate the hours of the day. Or it could operate an automaton such as a statue of Heracles, who would strike a bell with his club at each hour. Various devices were available, but there was another major problem that had to be met.

In antiquity daylight hours were divided into twelve equal parts, which naturally varied in length according to the season of the year. A basic difficulty with all water clocks was that they had to indicate the passage of the hours by dividing into twelve equal parts the period from sunrise to sunset and from sunset to sunrise. These periods varied from month to month as the days altered in length through the year. To allow for these seasonal hours, several adaptations in the inflow clepsydra were devised. In one of these variants, the zodiac clock described by Vitruvius, the flow was regulated by altering the depth of the outflow hole near the bottom of the constant level tank. In such a case, the orifice might be made in a circular plate, set in the tank wall so it could turn, and made waterproof around its edges. By turning the plate about one degree a day, so as to make one turn a year, and carefully adjusting its radius and the depth of its center below the surface, the rise and fall of the hole could give just the right sort of variation in the speed of the flow through the orifice. One doubts whether the device was ever much more than a pipe dream, for the difficulty of engineering such a turning plate or similar device, and of calculating its size, are very considerable and probably near the margin of Greek competence in science and technology. In the case of the Tower of the Winds, the relatively inaccessible placement of the constant level tank in an upper chamber of the round tower would virtually rule out this possibility.

In another solution, the float height in the cylinder was measured not on a single scale, but on a series of scales that could be changed each week or month, or varied continuously on a turning cylinder. It is plausible that some such scheme could have been used in the Tower of the Winds.

Yet another device offers even more promise. In the anaphoric clock, possibly invented by Hipparchos (ca. 140 B.C.) and described in detail by Vitruvius, the problem of the seasonal hours is given an elegant astronomical solution rather than an *ad hoc* change of scale or of water flow. The rise of the float within the cylinder had to be converted to a slow rotation of exactly one turn in 24 hours. This could have been effected by use of a rack and toothed pinion, or better, as in the account of Vitruvius, the float might have been connected to a sandbag counterpoise[25] by means of a string or soft bronze chain running around a wooden roller or a metal axle turning on a horizontal axis. The axle is then used to turn a large bronze disc mounted on its end and visible to the spectator through a "window" of reference wires. The disc is engraved with a celestial map in stereographic

[25] The use of a sandbag is a hallmark of authenticity in this description by Vitruvius. The counterpoise weight has to be carefully adjusted to be as small as possible in order to waste a minimum of the available force; on the other hand it has to be greater than the weight of the float in water, so that it can pull the dial backwards when the clock is rewound. Only in this condition will there be stability.

projection, showing all the stars and constellations from the north celestial pole as far south as the Tropic of Capricorn. Among these is a circle representing the ecliptic, surrounded by the zodiacal constellation, and pierced by a series of holes into which can be plugged a depiction of the sun at its proper place for the time of year—the plug being moved to the next hole every day or two days. Thus as the disc makes its daily rotation, the heavens will seem to the spectator to simulate their apparent diurnal motion.

The anaphoric disc is therefore very similar in character to the well-known astrolabe, and like an astrolabe it may be used to show the seasonal hours.[26] The window in the reference wires indicates the horizon for Athens in this case, and the curved wires mark the hour lines just as on an astrolabe, or more familiarly as on one of the common spherical or conical skaphe sundials of the period. As the image of the sun moves across these wires by day or night it shows the time as surely as the shadow on a sundial; moreover the anaphoric disc has the elegance of showing the position of all the stars in the daytime and the sun by night. Thus the anaphoric clock, in addition to telling the time, gave a quite theatrical simulation of the known universe. One might make much of the possible usefulness of such a display, perhaps to astrologers wishing to cast a nativity occurring in the daytime, but as one of us has argued elsewhere[27] this sort of sideshow has been a constant and attractive preoccupation of man from earliest times down to the Great Clock of Strassburg and the most modern Zeiss planetarium. Consequently we feel that, in this spirit, the entire construction of the Tower of the Winds is to be taken as an exuberant *tour-de-force*, symbolizing the cosmos and the elements and exhibiting them to a wondering public, rather than to those seriously concerned with the practical value of knowing the time of day or night and the direction of the wind. In this case the anaphoric clock is the most likely candidate for the display device connected to the clepsydra cylinder.

Remarkably, a fragment of such a Roman anaphoric clock dial has survived. About 1900 the Salzburg Museum purchased a bronze wedge-shaped fragment from workmen who had apparently found it in the neighborhood of Salzburg, near some Roman remains discovered during the digging of house foundations. It was published in 1902,[28] and correctly identified by Rehm as a portion of an anaphoric clock plate of monumental size—the radius of the disc when complete must have been more than 60 cm. and its weight over 88 pounds. The bronze fragment, about a quadrant of that part of the disc lying within the zodiac circle, is engraved with figures of the constellation with their names inscribed in Latin, and it contains a ring of sun-plug holes at two-day intervals. On the back of the disc the names of the zodiac signs and month names are also given in Latin; the form of the letters was judged to be that of the first two centuries A.D.

An anaphoric disc of this size and weight in bronze must have been provided with suitable support and bearings. The end of the axle would have been enlarged, probably by a wooden barrel, to produce a diameter about one quarter of the height of the cylindrical water receiver; this was necessary so that a day's rotation would correspond to a rise of the float through the entire height of the cylinder from bottom to top. It is perhaps worth remarking that the cylinder must be wide enough to contain a large float, since the force available is provided only by the difference between the weight of the float in air and its weight in water.[29] A strong force is required to turn such a heavy disc. Friction at the bearings would be considerable, especially with an axle thick enough to support a massive bronze disc without bending.

Such a disc *may* have been the display device used in the center of the Tower of the Winds. It would have been rotated once a day by means of a fine bronze chain running in pulleys clamped to collars on the lead pipe lying in the groove in the floor. The two side pedestals provided support for both the anaphoric disc and the window of

[26] For a comparison between the anaphoric clock and the astrolabe, see Singer, Holmyard and Hall, *A History of Technology* III (Oxford 1957) 605.

[27] Derek J. de Solla Price, "On the Origin of Clockwork, Perpetual Motion Devices and the Compass," *U.S. National Museum, Bulletin* 218, Smithsonian Institution (Washington 1959) and also "Automata and the Origin of Mechanism and the Mechanistic Philosophy," *Technology and Culture* V (1964) 9-23.

[28] E. Weiss and A. Rehm, "Zur Salzburger Bronzescheibe mit Sternbildern," *JOAI* 6 (1903) 32-49, and Taf. v.

[29] It follows from the considerations in n. 25 that the available force must be such; it is, of course, equal to the weight of the water displaced by the float when fully immersed, i.e. to the weight of its volume of water.

hour-marker wires, and since these were also connected to the water supply, fountains undoubtedly spurted from them. The back column was also used for support but it was not supplied with water. Decorative sculpture, appropriate to the chamber, would have surmounted the three pedestals.

A restoration of the interior of the Tower of the Winds cannot be definitive, but, as we stated at the beginning of this article, a restoration consistent with the archaeological findings and the technology of the period is possible and instructive. In pl. 118, figs. 18, 19, we have restored Poseidon as the central figure with Heracles and Atlas holding the window of reference wires in front of the rotating anaphoric disc. The fountains played into a central basin which was located over the central drain hole. Since the center area was also supplied with water, a fountain apparently also emerged from the central basin. The entire display was protected from curious Athenians by the marble railing. In this reconstruction the position of the sun on the anaphoric disc shows that it is approximately two and a half hours after sunset in late summer.

Upon entering the Tower of the Winds an Athenian would have beheld an amazing display of technical virtuosity; in the center of the Tower stood a bronze representation of the heavens, with the constellations and the sun imperceptibly rotating and duplicating their observable transit across the sky. As the sun moved with the anaphoric disc, it passed behind a grid of metal wires indicating the hours of the day and night. At either side, fountains played into a central basin which in turn spouted a jet of water before the solar disc. The theatrical nature of this lavish display was consistent with the exterior decoration of the Tower. All the sundials were surmounted by reliefs, personifications of the eight winds, and high atop the Corinthian roof finial stood a bronze Triton wind-vane with a rod in his outstretched hand rotating and pointing to the wind that was blowing.

We live in an era in which we accept science and technology as commonplace, and we expect them and our architecture to be efficient and functional. The Athens of Andronikos was a place of wonder and beauty, and it was a time to marvel at the achievements of mathematicians and astronomers —a time to build and admire a Tower of the Winds.

APPENDIX

On the exterior of the Tower of the Winds we note one feature that has not previously been remarked or published. On the side of the cylindrical tower there are the remains of what must have been a most striking and elegant sundial (pl. 113, fig. 11). This is a symmetrical dial of southern aspect, like the dial above it, one of the eight with which each wall of the octagonal tower is decorated, below the figure of the appropriate wind, Notos. In the case of this newly-discovered ninth specimen, the dial is made striking and unusual by being delineated on a convex cylinder rather than a plane wall.[30] The existence of the dial implies that, when newly constructed, the Tower was accessible from the south, without intervening buildings or elevated aqueduct. It also implies that the cylindrical tower could not have had an exterior entrance of any considerable size, even in the portion that is now lost, except for a possible trapdoor in the roof.

Of the three windows now present in the north, south and west walls of the octagon, none seems to be original.[31] The northern window is symmetrically placed in its wall, in the middle of the sundial, and just below the figure of Boreas. This sundial is unique in that its center is blank—because the sun becomes northerly only near sunrise and sunset in part of the year. The western window is placed to one side of center at the same height, and causes the loss of an important part of its dial pattern. Clearly the window had been created later by the removal of one of the original blocks. Apparently an effort was made to remedy this, perhaps during the fitting of the new bronze gnomons by Palaskas in 1845-1846.[32] During the present in-

[30] Examples are known for a sundial on a curved surface other than the usual spherical or conical concavity. Vertical concave cylinders are known from Volubilis and Rome (*CIL* VI 2306, cf. 32504, I² p. 280 n. xxiii B) and from the Villa Scipio near Naples. A dial on the convex surface of a sphere was excavated by Blegen at Prosymna (Nauplia), Carl W. Blegen, *AJA* 43 (1939) 410-444.

[31] In this opinion we have to differ from Robinson who considered the south window to be original.

[32] *Praktika* (1845-46) 234-235 and 269; (1846-47) 318-321. Perhaps it should be added that there are no grounds whatsoever for believing a persistent rumor that the dials on the Tower of the Winds were a later addition. The eight major dials are described by Stuart and Revett (*op.cit.* supra n. 1) as follows: "It is observable that not only the Hours of the Day, but the Solstices also, and the Equinoxes are projected on these Dials; and that the longest as well as the Shortest Days, are divided alike into twelve Hours" (I, chap. III, p. 20).

vestigation a thin, light-colored slab of marble, engraved with the missing sundial lines, was discovered among fragments lying on top of the shelf in the cylindrical tower. A photograph published in 1902[15] shows the slab in place, held in position by metal clamps inserted in square holes to the left and right of the slab and its adjoining blocks; apparently the replacement slab was too thin to keep safely in place, and a new restoration is needed. The southern window is lower and opens into the top surviving course of the cylindrical tower. It is asymmetrically placed, and careful examination showed that it had also been formed by the removal of an original block. The fact that this window adjoins the *Mihrab*, and was at eye height in Islamic times, makes it probable that this was a later adaptation for the Turkish *Teckeh*. Certainly it is shown, though slightly misplaced to the left of center, in *Views in Greece* by Edward Dodwell (1821) in a print showing the dervishes within the building (pl. 118, fig. 20). High on the right is the western window.

It is worthy of special note that the Tower of Winds is among the few buildings of antiquity known to have been designed by a person whose competence in classical geometry is otherwise verified. Andronikos is identified by Vitruvius and by Varro as the designer of the Tower, and the same name occurs on an elegantly conceived multiple sundial found in the sanctuary of Poseidon on the island of Tenos.[33] On both, the inscribed lines marking shadow lengths have the same profile—a triangle, about 2.5-3 mm. wide at the surface and about 1-1.5 mm. in depth. The Tenos dial shows an economy of geometrical construction which gives it mathematical elegance, and we shall now show that the floor plan of the Tower of the Winds contains this same mathematical economy and elegance.

Although it is clearly visible in the excellent floor plan supplied by Stuart and Revett,[34] it is surprising that the constructional geometry does not seem to have been previously noted. Perhaps the obvious symmetries of the precise octagonal shape have drawn attention away from the other alignments. The outline of the base masonry consists of a regular octagon with protuberances for the cylindrical water-tower and for the two entrance porticos. That of the water tower is an exact semicircle, while those of the porticos extend precisely to the intersection of the adjacent sides of the octagon; the pillars of the porticos are tangent to the same lines extended from the adjacent sides. The area of the floor of the Tower itself is a regular octagon formed by the inside edges of its walls. It is constructed from the base octagon by joining midpoints of alternate base sides to produce a pattern dominated by squares diagonally contained within squares. One can only hazard a guess as to whether the square-within-square pattern is linked in any way with the known conventional diagrams used in later times to symbolize the relation between the Aristotelian elements,[35] and perhaps even that used for the presentation of the twelve houses in a horoscope.[36] Certainly the use of the element diagram would be particularly appropriate in a structure combining representations of the winds and the universe with water fountains, and perhaps illuminated by the flames of oil lamps.[37]

As further points of geometrical design, it may be noted that the cylindrical water tower, though semicircular at base level, has an interior containing exactly three-quarters of a circle; furthermore its outer diameter coincides with the inside length of one of the octagonal walls and also with the diame-

[33] *IG* xii, 5, 891 and xii Suppl. (1939) 139, no. 891. See also *MusB* 10 (1906) 353-361; 11 (1907) 51. The dial in question is among the few classical examples showing considerable geometrical complication, and among the very few carrying the long dedicatory inscription. For discussion, but not a complete geometrical elucidation, see H. Diels, *Antike Technik* (Leipzig and Berlin 1920) 171-174 and pl. xiii.

[34] The reader should perhaps be warned that the Stuart and Revett ground plan is in fact a conflation, showing floor level in one part, lower cornice in another, and upper cornice in a third; it is carefully explained as such in the accompanying text. Unfortunately the plan has been frequently reproduced without the explanation (e.g. in Baumeister, *Denkmäler des klassischen Altertums* [1889] fig. 2368, p. 2114) and the problem of the remaining traces may thereby have been made a little more difficult.

[35] It may well be that the underlying square-in-diagonal-square construction had, for the maker, a philosophical significance which is responsible for his decision that there were to be only eight winds symbolized by the Tower. Vitruvius makes a great point of Andronikos having promulgated this system, presumably over opponents who saw the number of winds as otherwise arbitrary. See J. G. Wood and G. T. Symons, *Theophrastus of Eresus on Winds and on Weather Signs* (London 1894) 77-88, and A. Rehm, "Griechische Windrosen," *SbAkBayer, Phil.-hist.kl.* (Munich 1916).

[36] This form of diagram is verified only by sources much later than Hellenistic.

[37] In its original state the interior of the building was lit only by the two open doors. Artificial illumination would therefore be necessary if the internal apparatus was used as a night clock.

ter of the inner ring of the circular balustrade that stood in the center of the tower. It is also possible, but not entirely probable, that the outer line of the walls could have been produced by further such alignments, thus determining geometrically the thickness of the masonry blocks of the wall. It is, however, only too easy to find such alignments, even in a rather random structure, if one draws enough lines—as is well known from the efforts of pyramidologists and Stonehenge-manipulators—but such refinements are seldom strong enough to carry overwhelming conviction. In this case there is certainly sufficient evidence to show that, over and above the necessities of an octagonal structure, there was a great deal of drawing-board descriptive geometry, displaying a neatness and economy of construction which has little room for arbitrary placings.

Though the plans of foundations and walls show great regularity in geometrical layout, almost nothing of this was carried over into the masonry, which appears to have been dominated by economy in the use of available blocks of stone. We show (pl. 117, fig. 14) a complete plan of the individual stones of the floor and their joins, and it will be observed that within the constraints of the octagonal outline there remains only vestigial symmetry. Clearly the large central block, an elongated octagon, was set down first at the exact center of the foundation, and it was then accurately aligned on a north-south axis, as is testified by an engraved line running along it to the north of the central hole.[38] Judging from the pattern of the joins, the blocks immediately north of this center were next laid, then those to the northwest and so counterclockwise around the octagon. By the time a full circle was made, enough errors had accumulated to produce a very bad fit between the northeast and north sections.

It is interesting that, while the three protuberances on the octagonal base have all been incorporated as integral parts in the construction, the masonry of the portico bases is rather regular and symmetrical, whereas that of the cylindrical tower is highly irregular. It would seem that the interior of the water tower was constructed less with regard to visible neatness than to strength, in keeping with the supposition that it held machinery and was not accessible to the public.

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[38] This line may well be that used by Andronikos to set the axis of the Tower exactly along the line of meridian. Such accuracy was essential for the proper working of the exterior sundials and, in fact, was achieved.

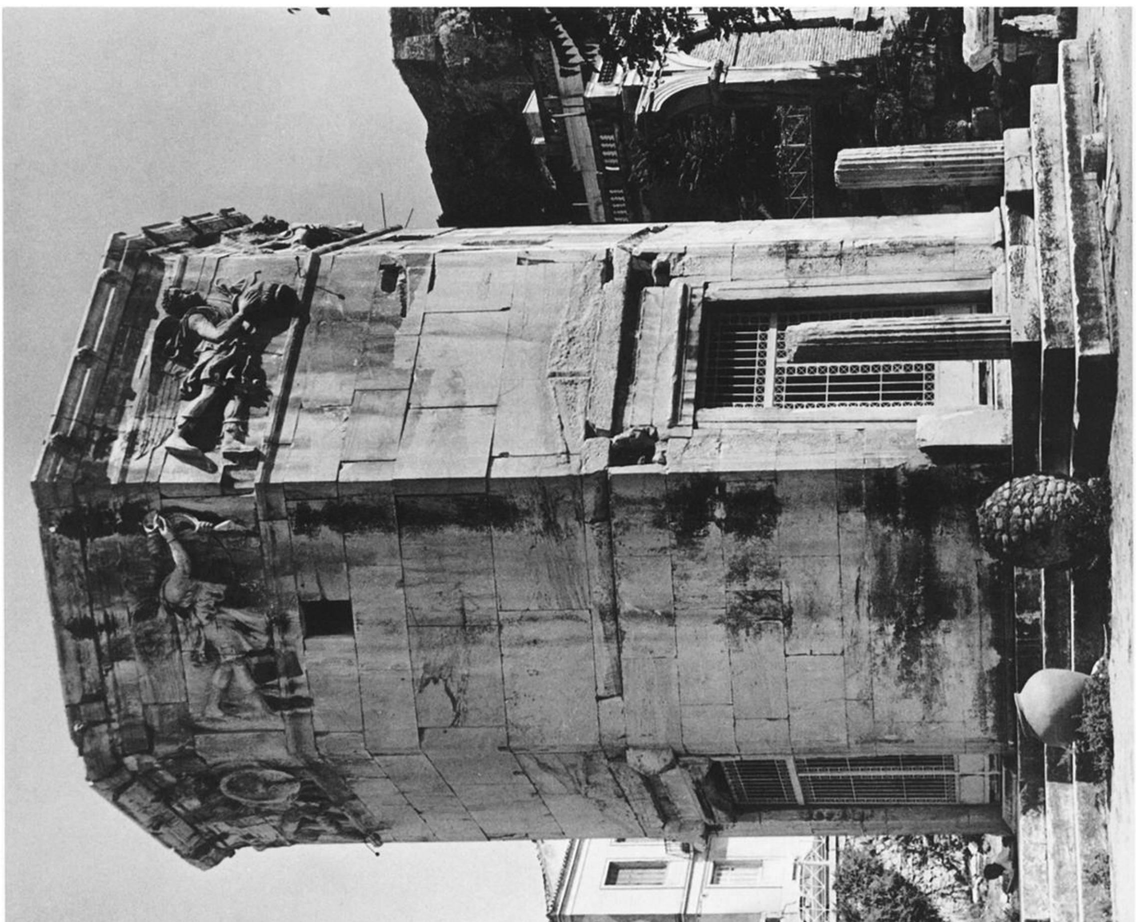

Fig. 1. Tower of the Winds from north

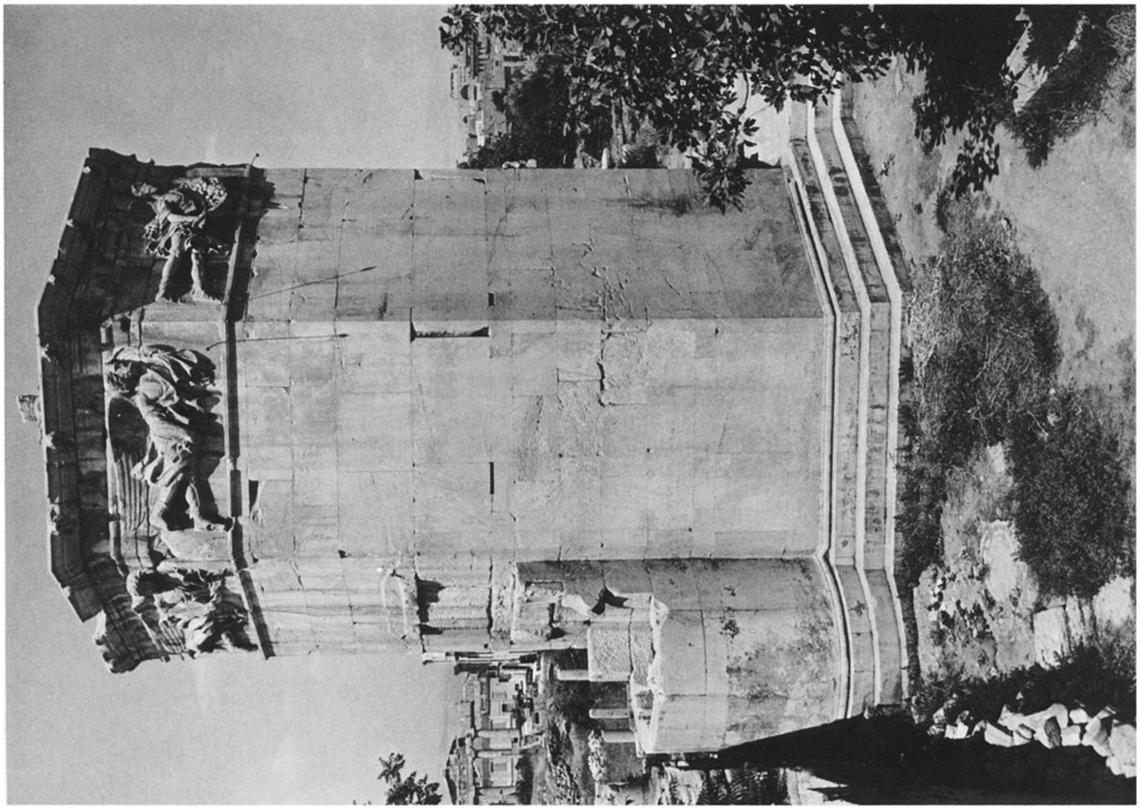

Fig. 2. Tower from southeast

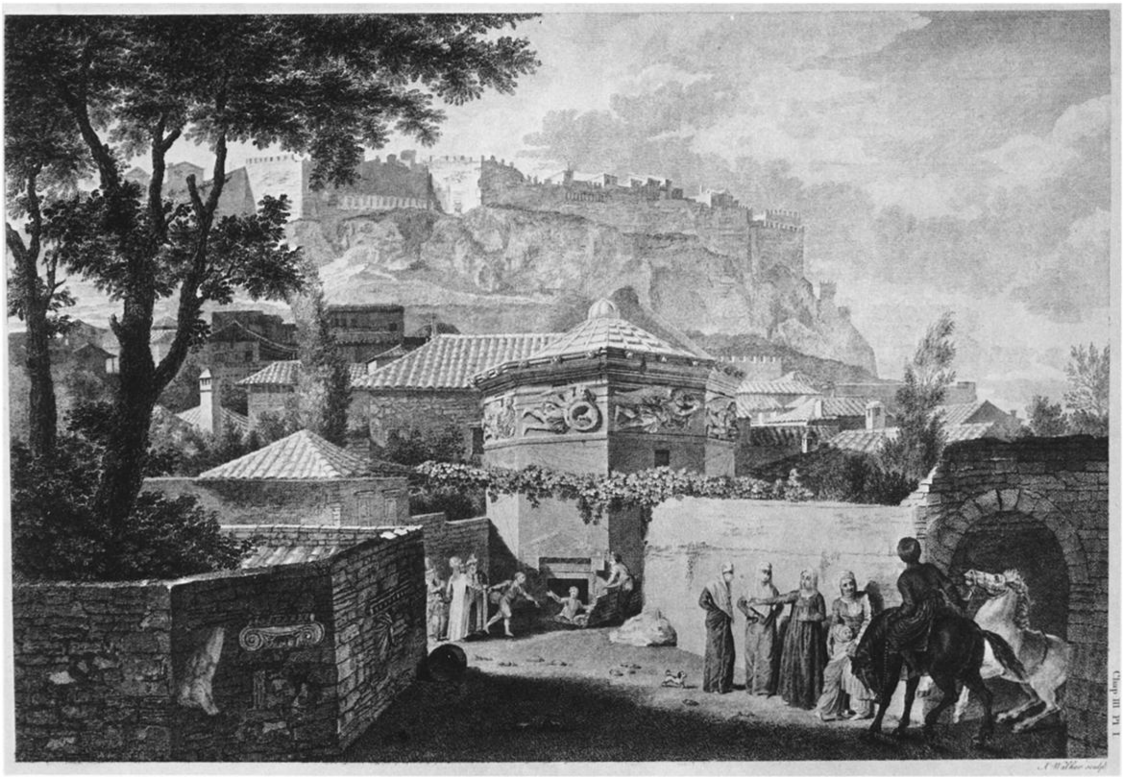

FIG. 3. General view of Tower: Stuart and Revett, pl. I

FIG. 4. Reconstruction: Stuart and Revett, pl. II

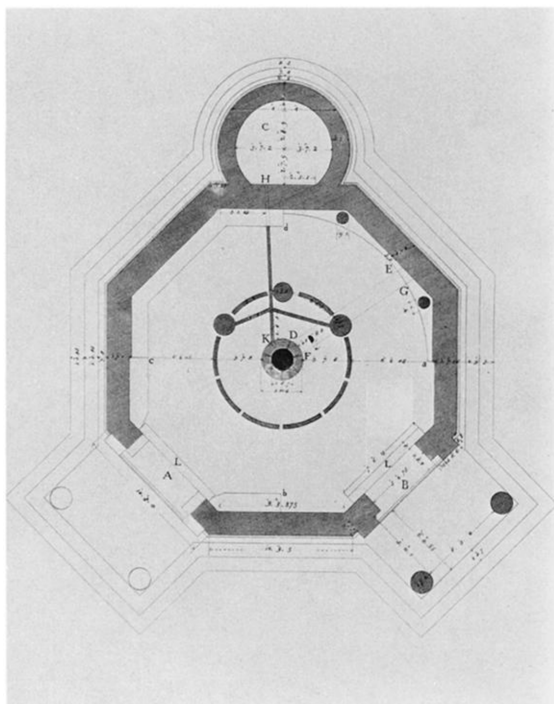

FIG. 5. Floor plan: Stuart and Revett, pl. III

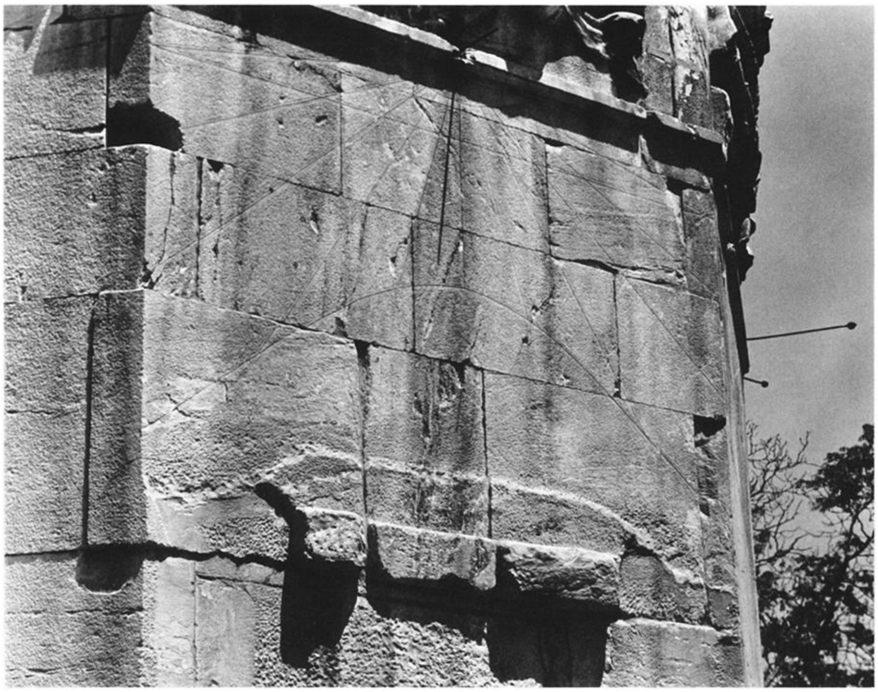

FIG. 10. Sundial on south wall

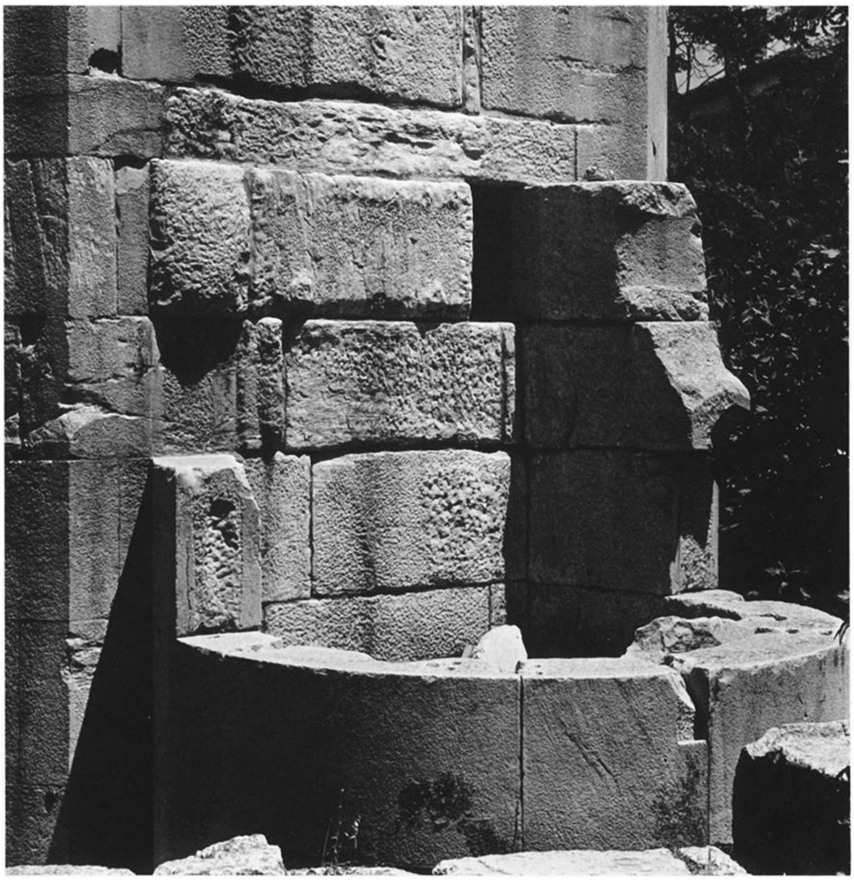

FIG. 11. Cylindrical water tower with traces of ninth sundial at lower left

FIG. 6. Boreas, the north wind; Skiron, the northwest wind

FIG. 7. Zephyros, the west wind; Lips, the southwest wind

FIG. 8. Notos, the south wind; Euros, the southeast wind

FIG. 9. Apeliotes, the east wind; Kaikias, the northeast wind

Fig. 13. Interior of octagonal tower with doorway to cylindrical water tower at left

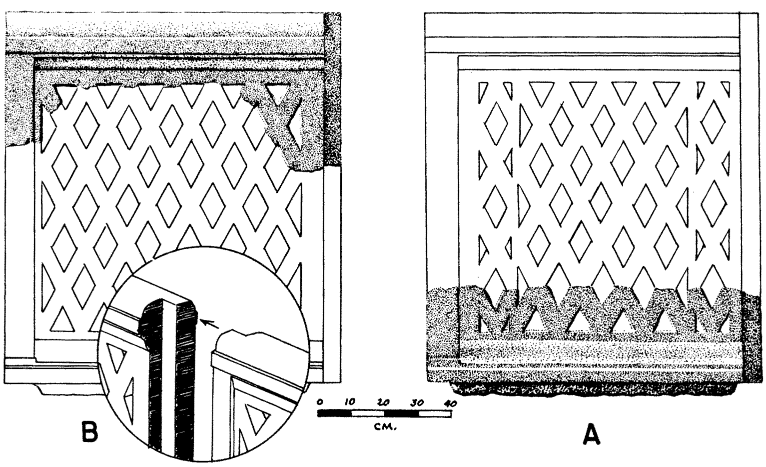

Fig. 16. Reconstruction of railing

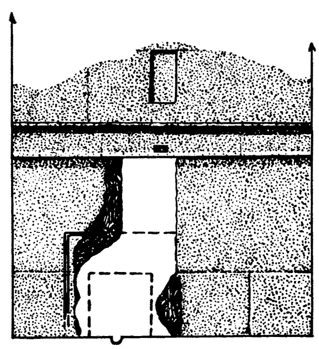

Fig. 17. Doorway, cylindrical water tower

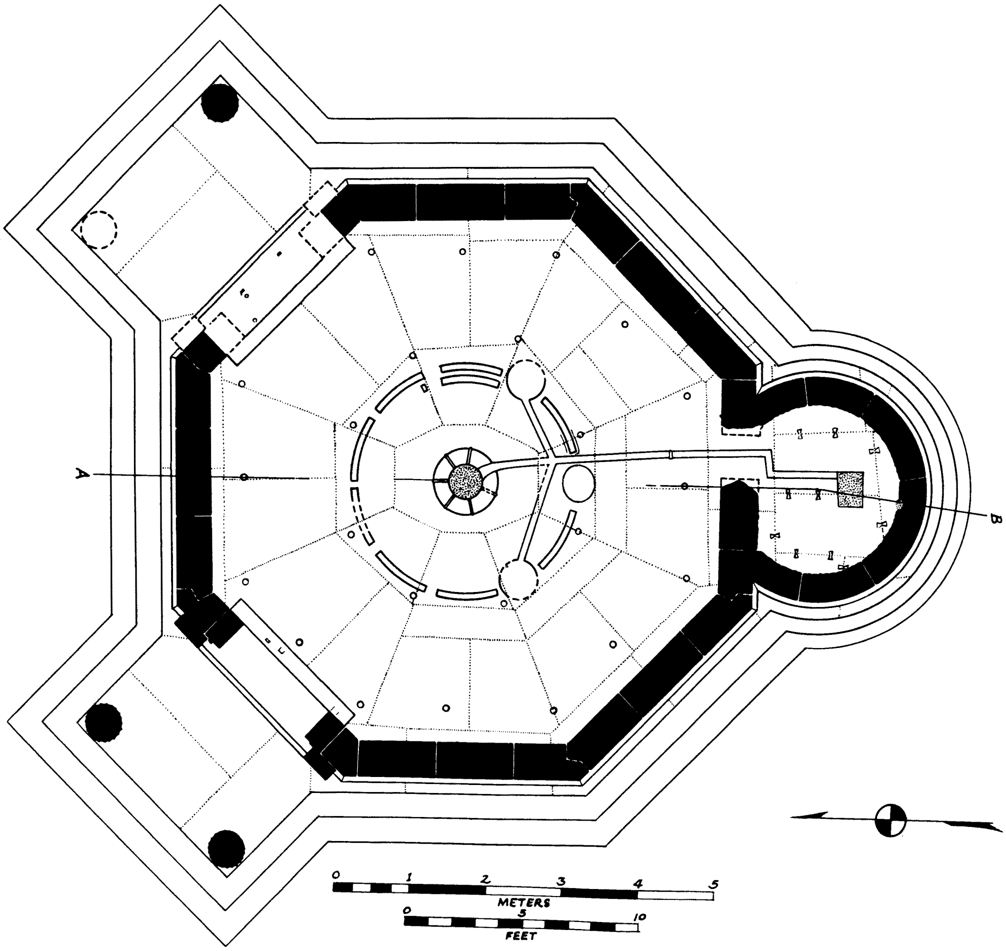

FIG. 14. Floor plan

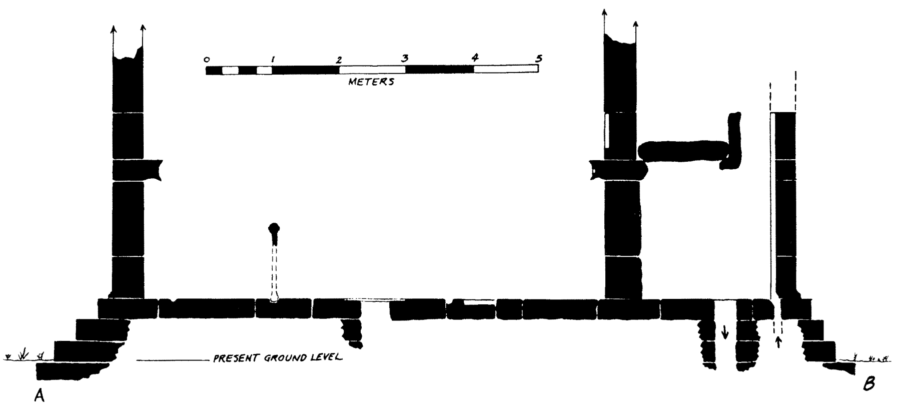

FIG. 15. Elevation of lower section

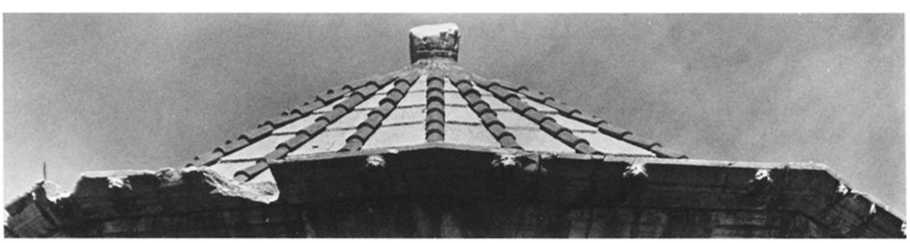

FIG. 12. Roof finial and marble roof slabs

Fig. 18. Cutaway reconstruction of water clock

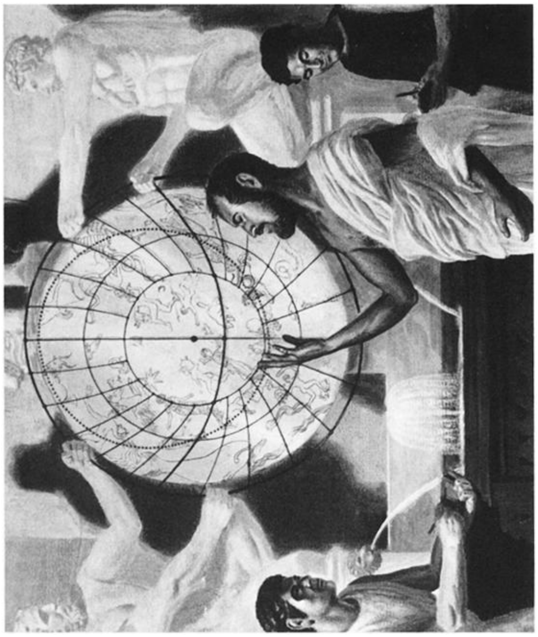

Fig. 19. Reconstruction of water clock with anaphoric disk

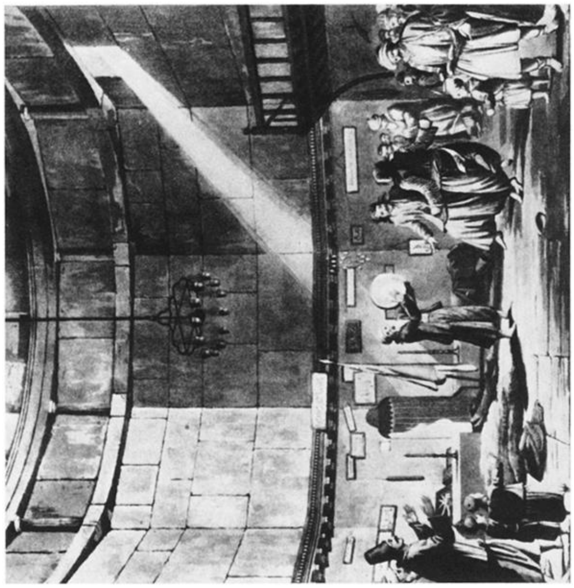

Fig. 20. Interior of Tower when used by whirling dervishes