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The Karnak Clepsydra and its Successors: Egypt's Contribution to the Invention of Time Measurement

Summary

The invention and establishment of the water clock in Egypt, at first glance, seems to be one of the best-documented developments in the history of ancient technology. A closer look at these clocks, however, reveals that their form and function have not yet been described sufficiently. Meanwhile, acquisition of three-dimensional data enables novel analysis of the preserved examples scattered all over the world. Regarding the fragmentary condition of most of the clocks, 3D scans are indispensable to investigate developments and functions of particular examples more closely and to ascertain the knowledge that existed about fluid dynamics around 1500 BC.

Keywords: Egypt; time measurement; water clock; 3D scans; transfer of technology

Die Erfindung der Wasseruhr in Ägypten scheint auf den ersten Blick so gut dokumentiert zu sein wie kaum eine andere Entwicklung der antiken Technikgeschichte. Betrachtet man jedoch diese Uhren näher, so zeigt sich, dass ihre Form und ihre Funktionsweise längst nicht ausreichend beschrieben sind. Inzwischen macht die Aufnahme dreidimensionaler Daten neuartige Analysen der erhaltenen Stücke möglich, die heute auf der ganzen Welt verstreut sind. Im Hinblick auf den meist fragmentarischen Erhaltungszustand der Uhren sind 3D-Scans unerlässlich, um Entwicklungen und Funktionen der einzelnen Instrumente genauer zu untersuchen und so zu erforschen, welches Wissen um 1500 BC über das dynamische Verhalten von Flüssigkeiten herrschte.

Keywords: Ägypten; Zeitmessung; Wasseruhren; 3D-Scans; Technologietransfer

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Before the origin of time measurement in antiquity can be addressed, we must realize that the first clocks had only an extremely limited effect on people's lives. This may come as a surprise, given the importance that we attach nowadays to this instrument. Unlike today, however, ancient timetables and time clocks did not provide a rhythm to daily life.¹ Time measurement followed different rules, as the introduction of the clock in Rome demonstrates. Pliny the Elder's account gives a good impression of the implementation of this instrument and can be considered exemplary of antiquity in general:

Marcus Varro records that the first sundial in a public place was set up by the consul M. Valerius Messalla, on a pillar beside the Rostra, after the capture of Catania in Sicily during the first Punic war; and that it was imported from Sicily thirty years after the traditional date of Papirius' sundial, in 263 BC. The lines of this sundial did not agree with the hours, but they were followed for 99 years, until Q. Marcius Philippus, who was censor with L. Paulus, placed a more precisely constructed one next to it; a gift which was the most appreciated action of his censorship. (215) Even then, however, the hours remained uncertain on cloudy days until the next lustrum. Then, Scipio Nasica, the colleague of Laenas, was the first to use a water-clock [clepsydra] to mark the equal hourly divisions of night as well as day. He dedicated this clock, which was installed under cover, in 159 BC. For so long had the Roman people been without a means of dividing their day!²

A lack of precision was of no consequence, to Pliny's astonishment, since the Romans had lived quite well by a miscalculated clock for a hundred years. On the other side, Pliny stressed an important point – people appreciated the clock as a singular gift. In evaluating time measurement in antiquity, both aspects need to be taken into consideration, so that a standard different from the modern one is applied with regard to the importance, value, and accuracy of clocks within their inherent contexts. Clocks had

- 1 Historians and sociologists agree that the concept of time changed fundamentally in the medieval age. See, for example, the remark by Lewis Mumford that the mechanical clock and not the steam engine was the key invention of the modern industrial age; see Mumford 1934, 12–18; cf. also the historical survey by Dohrn-van Rossum 1995, 11–23, 202–295, 318–321.
- 2 Beagon 2005, 106. – M. Varro *primum statutum in publico secundum Rostra in columna tradit bello Punico primo a M. Valerio Messala cos. Catina capta in Sicilia,*

deportatum inde post XXX annos quam de Papiriano horologio traditur, anno urbis CCCCLXXX. Nec congreuebant ad horas eius lineae, paruerunt tamen ei annis undecentum, donec Q. Marcius Philippus, qui cum L. Paulo fuit censor, diligentius ordinatum iuxta posuit, idque munus inter censoria opera gratissima acceptum est. Etiam tum tamen nubilo incertae fuere horae usque ad proximum lustrum. Tunc Scipio Nasica collega Laenati primus aqua divisit horas aequae noctium ac dierum idque horologium sub tecto dicavit anno urbis DXCV. Tam diu populo Romano indiscreta lux fuit.



Fig. 1 Athenian clepsydra.

not been necessary in everyday life, as a rule, because people relied upon observations of the sun and the stars, as well on estimations of the length of their own shadows.³

Nevertheless, monitoring the passage of time in detail was necessary in some cases. Unfortunately, these cases also contain the origin of a common misconception: the distinction between a true clock and a stopwatch.⁴ The problem is complicated further by the use of the word ‘clepsydra’ to refer to both devices. The most famous example of an ancient stopwatch of this type is the Athenian clepsydra,⁵ an instrument solely destined to limit the length of speeches at the law courts in Athens (Fig. 1). Similar instruments were used to divide vigils into equal lengths in the Roman army⁶ and in second millennium Mesopotamia,⁷ and to regulate irrigation intervals in northern Africa.⁸ Such instruments differed fundamentally from a real clock in one respect, they did not reveal the actual time, but rather the length of a (repeated) interval, and this makes all the difference. This kind of clepsydra consists of a simple vessel with a small outlet at the bottom that is either filled with water or placed empty into a larger vessel filled with water. In the former case, the interval in question lasts until the vessel is emptied, as with the Athenian clepsydra; in the latter, the interval lasts until the inflowing water submerges the so-called water-sinking bowl.⁹

3 Bilfinger 1888, 75–78.

4 For the distinction between a stopwatch, which is quite easy to construct, and a clock, which requires a high degree of sophisticated skills and preconditions with regard to antiquity, see for example Bilfinger 1886, 6.

5 See Last 1924, 169–173; Young 1939, 274–284.

6 Aen. Tact. XXII, 24; cf. Diels 1920, 195 n. 1.

7 See Hunger and Pingree 1989; Thureau-Dangin

1932, 133–136; Thureau-Dangin 1937, 51, and Al-Rawi and George 1991/1992, 52–73, while the work of Neugebauer 1947, 37–43, is still fundamental. The Mesopotamian water clock was recently the subject of several articles that provide an overview. Nevertheless, the authors do not discuss the distinction between a clock and a stopwatch, and hence do not even take into account that the Mesopotamian

It is often overlooked that in contrast to a stopwatch, the construction of a properly functioning water clock requires not only a high level of theoretical knowledge and practical abilities, but also a context in which the demand for such a clock exists, as well as the conditions to enable time measurement. In short, the amount of knowledge required before development of a water clock could begin was far more advanced than it appears at first glance. For example, time units had to be defined: in the case of ancient Egypt, twelve hours per night/day were the smallest measureable units.¹⁰ With regard to antiquity in general, this meant dividing the shifting time period between sunrise and sunset into twelve parts and operating with so-called unequal or seasonal hours.¹¹ As a consequence, a clock in antiquity had to show different hours over the course of the year (and, in an ideal case, each day): long daylight hours in summer and short daylight hours in winter, and of course vice versa at night. Only for a very limited period at the equinoxes in spring and autumn are the hours of day and night equal. Therefore, the geographic latitude had to be considered too, since the latitude determines the rising and setting of the sun. To put it the other way around, determining the running time of such a clock allows us to determine its appropriate latitude, or the latitude of its original site location.¹² The removal of such a clock from the particular latitude for which it was manufactured would, inevitably, result in an incorrect display.

A working (stable) calendar is an absolute necessity in order to determine regularities concerning the increase and decrease in the length of the hours over the course of the year reciprocal to a specific latitude; it provides a clear concept not only of periodic months, but also of each month, with corresponding hours of an appropriate length. Most ancient calendars were based on the lunar cycle, however, even with its inherent irregularities.¹³ For this reason, they created unfavorable framework conditions. Only in ancient Egypt is an entirely different situation apparent. According to the Egyptian civil calendar, a year of 12 months, at 30 days each, plus 5 additional 'epagomenal' days, results in 365 days in total. The civil year, thus nearly approaches the dimension of the modern calendar year of 365 $\frac{1}{4}$ days, although it lacks the addition of a leap-year day

sources may refer solely to stopwatches; cf. Brown, Fermor, and Walker 1999/2000, 130–148; Michel-Nozières 2000, 180–209; Fermor and Steele 2000, 210–222; Falk 2000, 197–132 and a more critical voice Høyrup 1997/1998, 192–194.

8 Diels 1920, 196–197 pl. XVI.

9 See Smith 1907, 319–334 fig. 2; Turner 1984, 9–11; Brown 2000, 119–120.

10 Cf. Borchardt 1920, 3–5.

11 This concept was used throughout antiquity, until the Middle Ages and the invention of the mechani-

cal clock, when these hours were gradually replaced by the equinoctial or equal hours common today; cf. Dohrn-van Rossum 1992; cf. for example, the mechanical clock by Giovanni de Dondi; Bedini and Maddison 1966, 1–69; cf. Flachenecker 1996, 391–398.

12 This has already been discussed in detail by Borchardt 1920, 17–19; cf. Hölbl 1984, 31, 35.

13 An early reference to the superior Egyptian civil calendar appears in Hdt. II. 4.

every four years. It follows that, beginning with the introduction of the civil calendar,¹⁴ Egypt provided calendrical conditions that encouraged the development of a clock to a much greater extent than Mesopotamia or Greece did. Given these challenges, however, there had to be a real need to measure time in order to engender a determined effort to construct a clock.

Only two devices were available for time measurement in antiquity before the invention of the mechanical clock, which took place at some point in the fourteenth century AD. Pliny refers to the differences between these devices: whereas sundials¹⁵ only work on sunny days, a water clock has the potential to operate independently from external circumstances. The operation of a sundial requires only sunshine and some kind of shadow-caster, combined with a few calculations, to form a time-measuring instrument. A water clock, by contrast, involves extending beyond observation, thus, creating a higher degree of abstraction: first, it requires the conceptual development of a device that is independent from its surroundings, and then it requires the conditions for the device's creation. As the invention of the water clock shows, both the concept and the conditions existed in Egypt before anyone came up with the idea of measuring time with a clock. In addition, the invention of the water clock occurred in response to a fundamental need.

As the quote by Pliny the Elder has already shown, Rome was without a doubt 'behind the time' in the second century BC as far as the invention and application of the water clock was concerned. Instead, another city played a leading role in technological innovation¹⁶ in early Hellenistic times, especially in the development of water clocks. The Roman author Vitruvius dedicates several chapters in his *De Architectura* to the description of water clocks¹⁷ – sophisticated and highly representative devices that he credited the famous engineer Ctesibius with inventing at the Museion in Alexandria during the reign of Ptolemy II. These clocks inspired admiration not only from Vitruvius but also from others throughout antiquity and beyond. However, as famous and

14 The exact date of the introduction of the civil calendar is still disputed; see Leitz 1989, 53–54.

15 The same applies, of course, for Egyptian star clocks on nights with a clear sky, the oldest time-measuring instruments of all. Without entering into a detailed study of Egyptian star clocks, it is worth mentioning that time measurement in Egypt not only started quite early, but also used a device that was limited to nocturnal use – a clear indication of the field of application of clocks in Egypt; cf. Leitz 1995.

16 Cf. for example Schürmann 1991; Argoud and Guilamin 1998; D. M. Lewis 2000, 631–648; Russo

2005.

17 Vitruvius IX, 8, 2–15. – “These same writers have also invented methods for assembling clocks that use water, Ctesibius of Alexandria first among them” (Rowland 1999, 116); for Vitruvius sources see Fleury 1998, 103–114; D. M. Lewis 2000, 361–369, gave an overview of the invention and development of water clocks in ancient times. Unfortunately, in his article he made no distinction between a water clock and a stopwatch like the Athenian clepsydra (see Fig. 1). Therefore, he fails to underline the unique role Egypt played in the development of water clocks.



Fig. 2 Karnak clepsydra.

sophisticated as the water clocks by Ctesibius may have been, the actual invention of this device took place more than a thousand years earlier, remarkably, in the same cultural area. Although Ctesibius' clocks left hardly any traces, except for descriptions made by authors like Vitruvius,¹⁸ pictorial reconstructions based on these descriptions turned out to be extremely formative. From the beginning, these pictorial reconstructions established the modern notion of ancient water clocks and their appearance.

As a consequence, the emergence of original fragments of Hellenistic water clocks in seventeenth-century Italy drew little attention.¹⁹ This initial lack of interest can be attributed to their fragmented condition and, therefore, to the common misinterpretation of the objects, but it continued later on because of their fragmented appearance. Only when G. Legrain discovered a nearly complete specimen in 1904, in the famous Karnak Cachette, did this type of water clock begin to attract researchers.²⁰ Examined first by G. Daressy²¹ in an article in 1915, the Karnak clepsydra (Fig. 2) undoubtedly constitutes the oldest preserved water clock, originating from the time of Pharaoh Amenhotep III (1379–1342 BC).²²

The famous Egyptologist Ludwig Borchardt was the first to recognize the fundamental importance of these pieces. Unaware of the article by Daressy, Borchardt published a thorough study in 1920 about time measurement in ancient Egypt that turned out to be perhaps the most influential and authoritative examination conducted in the

18 See Schomberg 2017.

19 Kircher 1654, 385; although Athanasius Kircher was the first to publish two fragments of water clocks and succeed in identifying them correctly ("probably a water clock"), his interpretation was not confirmed until the early twentieth century.

20 Cf. for the Karnak clepsydra: <http://www.ifao.egnet.net/bases/cachette/>, search term: 'clepsydra' (visited on 23/05/2018).

21 Daressy 1915, 5–16.

22 Cf. Warburton 2009, 134.

field of Egyptian time measurement to date.²³ Borchardt's rather condensed presentation has precluded any critical discussion of his groundbreaking investigation for almost a century, but such a discussion must now be the essential starting point for further examination of the present topic.

While Daressy focused only on the recently discovered Karnak clepsydra and a second vessel in the Egyptian Museum in Cairo, Borchardt took a much broader approach, using all of the means at his disposal. Just before his book was published, Borchardt learned of an inscription that provided a key to understanding Egyptian water clocks.²⁴ As he writes in a supplement to his book, K. Sethe had drawn his attention to a report inscribed at the tomb of an Egyptian official named Amenemhet.²⁵

This grave, which was discovered by fellaheen in 1885 at Sheikh Abd el-Qurna in western Thebes, is now lost. The only items preserved from it are a small fragment of the inscription, now in the Egyptian Museum Berlin, and two copies made immediately after the discovery.²⁶ Amenemhet, who lived under the pharaohs Ahmose I, Amenhotep I, and Tuthmose I, around 1500 BC,²⁷ explains in his inscription that he has recognized that the length of the night increases and decreases from month to month. For this reason, he has constructed an *Mrht* – an “instrument for telling time.”²⁸ This device, he claims, shows the hours precisely, has astronomical depictions on the exterior, and has no predecessors (although he had consulted older texts beforehand);²⁹ its water runs out through a single exit.

The significance of this inscription was revealed a few years later, when the aforementioned discovery of the Karnak Cachette brought to light the remains of a vessel that met all these conditions, as Borchardt and especially Sethe realized.³⁰ The Karnak clep-

23 See Borchardt 1920; as Borchardt explains on page 6 in note 1, he had had no access to the article by Daressy because of the war. In the same note, Borchardt also points out that his chapter on the Egyptian water clocks stems from a more detailed but only handwritten treatise he had been planning to publish. Unfortunately, he refrained from doing so. Borchardt's hitherto unpublished manuscript was discovered in the archive of the “Schweizerisches Institut für Ägyptische Bauforschung und Altertumskunde” in Cairo. Its publication is the subject of an ongoing *Topoi* project.

24 See Borchardt 1920, 60–63 pl. 18.

25 Sethe dealt with this inscription in an article published in 1920; cf. Sethe 1920, 114–115 n. 3; nevertheless, Borchardt partly disagreed with Sethe's conclusions; see Borchardt 1920, 61–62; the inscription has recently been reedited by A. von Lieven; see von Lieven 2016, 207–231.

26 Egyptian Museum Berlin, Inv.-No. 14470; see von Lieven 2016, 207–208 esp. n. 4; the copies were made by E. Schiaparelli and W. Golenischeff. Borchardt based his transcription on Golenischeff's copy.

27 Cf. Hornung, Krauss, and Warburton 2006, 492.

28 For the translation of this term see Borchardt 1920, 62 n. 4.

29 Cf. von Lieven 2016, 221: “[I] studied [?] by reading in all writings of the god's works.”

30 For the Karnak clepsydra cf. Daressy 1915, 5–16; Borchardt 1920, 6–7 pls. 1–3; Sloley 1924, 43–50; Sloley 1931, 174–176; Pogo 1936, 403–425; Chatley 1940, 68–72; Parker 1950, §207–208; Neugebauer and Parker 1969, 12–14; Desroches-Noblecourt 1976, 139–149, pl. 33; von Mackensen 1978, 13–18; Cotterell, Dickson, and Kamminga 1986, 31–50; Long 1989, 589–591; Mengoli 1989, 227–271; Clagett 1995, 66–73; Spalinger 1995, 111–114;



Fig. 3 Interior of the Karnak clepsydra.

sydra was found broken in pieces, and was made of alabaster. Its shape is reminiscent of a large flowerpot; the outside of this vessel has characteristic depictions in three horizontal rows and a vignette of pharaoh Amenhotep III. The vignette allows the clepsydra to be dated to the middle of the fourteenth century BC. The uppermost row shows decans and anthropomorphic representations of stars and planets depicted in barks. Below, in the middle row, are the more prominent constellations of the northern sky and deities on both sides. The bottom row has six frames, each displaying the king, flanked by two of the twelve gods of the months. The outflow aperture is located between two of the frames.

Twelve scales of various length, with hour markings, are inscribed on the inside of the vessel (Fig. 3). Above each scale, on the rim of the vessel, the name of the corresponding month is inscribed, with the god of that month depicted on the outside. The months containing the two solstices – and therefore the longest and shortest hours of the year – correlate with the longest and the shortest scale, respectively, while the months containing the equinoxes are represented by the medium-length scales (Fig. 4). The lengths of the other scales follow accordingly. At sunrise or sunset, the vessel could be filled with water, which flowed out gradually from the small aperture near the bottom of the vessel. The hour was obtained by comparing the dropping water level to the scales on

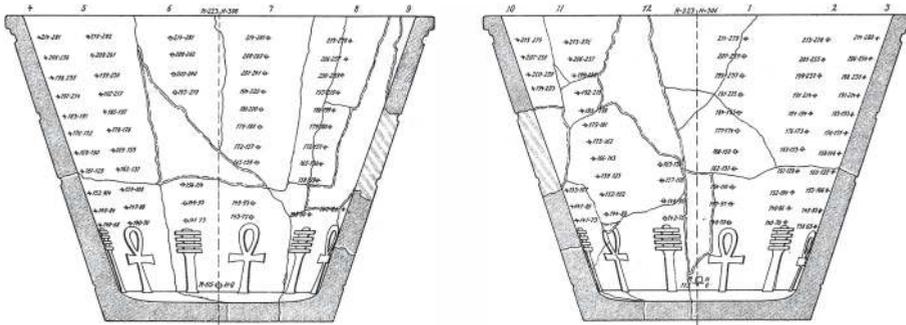


Fig. 4 Karnak clepsydra, scales.

the inside.

Having the Karnak clepsydra as a means of comparison made it obvious that several other collections contained fragments of Egyptian water clocks. The identification of these fragments was unmistakable: they shared not only the shape and the functional principle of the Karnak clepsydra, but also the depictions on its outside, in varying detail.³¹ Parallels to such depictions can be found in the astronomical ceiling decorations at the Tomb of Senmut and at the Ramesseum.³² All of them are based on an older tradition of ‘classical sky representations’ whose traces lead back to the Middle Kingdom.³³ Each of the Hellenistic pieces copies the depiction of the Karnak clepsydra accurately; some of them show the complete pattern of the clepsydra in three rows, while others reduce the decoration to the bottom row. Both versions existed in parallel in Hellenistic times.

Once there could be no doubt that these pieces of characteristic shape and decoration came from water clocks made in the tradition of the Karnak clepsydra from over a millennium earlier, the crucial question, according to Borchardt, was whether these kinds of clocks kept time properly.³⁴ Scholars have followed his lead since he first raised this issue in 1920, and they still focus on this question more or less exclusively, or confine themselves to an overview of the material.³⁵ Such means do not sufficiently interrogate Borchardt’s methods and procedures, however. This is by no means a criticism of his

Depuydt 1997, 110–119; Mills and Symons 2000, 18–20; <http://www.ifao.egnet.net/bases/cacheette/qv.clepsydre> (visited on 01/02/2018).

31 With one exception: a fragment in Cairo that stems from the time of pharaoh Necho II. The water clock fragment, discovered between 1929 and 1937 by P. Montet in Tanis, follows a different pictorial tradition; see Montet 1946, 35–39 pls. I–II.

32 See Neugebauer and Parker 1969, 8–62.

33 von Lieven 2012, 1–2; von Lieven 2007, 43; see J. F. Quack, *Beiträge zu den ägyptischen Dekanen und ihrer Rezeption in der griechisch-römischen Welt* (in prep.).

34 Borchardt 1920, 14.

35 Cf. for example the articles by von Mackensen 1978, 13–18, Hölbl 1984, 5–67, Cotterell, Dickson, and Kamminga 1986, 31–50, or Mengoli 1989, 227–271, and the overview by Lodomez 2007, 57–76.

accomplishments, but rather a call to reconsider our approach today, while still recognizing him as the most important forerunner in this area of study. Unfortunately, the way Borchardt expressed himself presents an obstacle to a critical analysis, even for native speakers. It, therefore, seems appropriate to first discuss his chapter on water clocks critically, and then focus on new research perspectives.

Borchardt's interest in water clocks must have been aroused more or less immediately after the discovery of the Karnak Clepsydra, as evidenced by the inventory book of the Egyptian Museum Berlin. In order to study these instruments, Borchardt endeavored to receive plaster copies of all Egyptian water clock fragments known at that time. The arrivals of these plaster copies are recorded as having occurred as early as 1911/1912, either as donations from other museums and researchers or as donations to the museum in Berlin from Borchardt himself. These copies formed the basis for his study and are still preserved in the Egyptian collection. They also denote the material basis available to Borchardt at the time. The collection comprises fourteen fragments, which according to Borchardt, originally belonged to twelve outflow water clocks.³⁶ The fact that this material basis has been significantly expanded since then is reason enough to reopen the issue of the Egyptian water clocks: new discoveries have led to knowledge of over thirty fragments, more than twice as many as Borchardt had at his disposal.³⁷

As simple as the water clock seems to be, on closer examination, it depicts a certain ingrained knowledge of fluid dynamics. Borchardt was the first to recognize that the shape of these water clocks revealed the application of a fundamental theorem in fluid dynamics, described for the first time in 1643 by the Italian scientist Evangelista Torricelli, and now known as Torricelli's Law. It states that the velocity v of a liquid flowing under the force of gravity out of an opening in a tank is jointly proportional to the square root of the vertical distance h between the liquid surface and the center of the opening and the square root of twice the acceleration caused by gravity, $2g$. In short $v = \sqrt{2gh}$, where g is the acceleration due to gravity. The exceptional importance of the Egyptian water clocks is that their design demonstrates the practical application of this theorem more than three thousand years before its theoretical formulation.

Applied to an open vessel filled with water and with an aperture at the bottom like the Egyptian clepsydra, or to an outflow water clock in general, Torricelli's law states that the velocity of the outflow is based on the water pressure inside. This pressure normally decreases as the water level sinks, and the outflow velocity drops accordingly.

36 All of these plaster copies conform to Borchardt's clock nos. 1–12 and are preserved in the Egyptian Museum, with the exception of one complete water clock—Borchardt's clock no. 11. This piece had been found in Rome and had belonged to the collections in Berlin since 1910, so Borchardt did not

require a plaster copy. It has since been lost; only a couple of photos have survived. One other water clock (Borchardt no. 13) has only a reference, since Borchardt already considered it lost at the time; for his compilation see Borchardt 1920, 6–10.

37 Cf. the catalogue in Schomberg 2017.

The problem for such an outflow water clock lies in ensuring constant water pressure inside and a steady outflow rate. The solution presented by the Egyptian water clocks is as simple as it is brilliant: reducing the circumference of a vessel and, hence, the water surface, to the shape of a truncated cone means that the sloping sides of the vessel (at a ratio of 1 to 3) can provide constant water pressure inside the vessel and consequently a steady outflow rate. This is the exact reason a cylindrical vessel is unsuitable:³⁸ the sinking water level would result in diminishing water pressure and therefore a declining outflow rate.

By applying Torricelli's Law, Borchartd³⁹ tried to calculate the actual accuracy of the Karnak clepsydra, as well as whether the designers of this clock had succeeded. Unfortunately, the outcome was disappointing. A vessel that would be able to manage a steady outflow has to have the shape of a fourth-order parabola, and the Egyptian water clocks lacked precision in this regard (Fig. 5): the vessels were too narrow at the top and too wide at the bottom. This would have caused the clocks to run too fast in the first half of the period of time to be measured and too slowly in the second. His calculations brought Borchartd to the realization that the Egyptian water clock was not able to display time correctly. In fact, he concluded:

This collection clearly shows that the ancients failed to divide the time consistently with their outflow clocks. The hours these clocks indicated during one and the same night or one and the same day were not consistent at all, but rather differed significantly [...] This must have had the consequence, for example, that not even midnight could be correctly determined with these water clocks, since the clock would have indicated it almost three quarters of an hour after its actual occurrence [...] The ancient [Egyptian] theory that the water flowing out of a round container with walls in a slope of 1:3 will drop at a consistent rate to a consistent level is therefore appreciably false.⁴⁰

38 Related to this, is the complete discussion of the water clock in ancient Mesopotamia, since the sources seem to suggest a cylindrical water clock; cf. for example the recent articles by Høyrup 1997/1998, 192–194; Fermor and Steele 2000, 210–222; and Brown, Fermor, and Walker 1999/2000, 130–148.

39 Although Borchartd did not mention his sources, Høyrup 1997/1998, 192, states that, “his choice of symbols shows that he has consulted the standard literature on hydrodynamics.”

40 Borchartd 1920, 15–16. “Diese Zusammenstellung zeigt deutlich, dass es den Alten nicht gelungen ist, mit ihren Auslaufuhren die Zeit gleichmäßig zu

teilen. Die Stunden, welche diese Uhren in einer und derselben Nacht oder in einem und demselben Tag anzeigten, waren keineswegs gleich, sondern erheblich verschieden, [...] Dies muss z. B. zur Folge gehabt haben, dass mit diesen Wasseruhren nicht einmal die Mitternacht richtig bestimmt werden konnte, da die Uhr sie beinahe $\frac{3}{4}$ Stunden nach ihrem wirklichen Eintritt angab [...]. Die Theorie der Alten, dass in einem runden Gefäß mit Wandungen in einer Neigung von 1:3 das auslaufende Wasser in gleichen Zeiten um gleiche Höhen sinkt, ist also beträchtlich falsch“ (translation from the German by Casey Butterfield).

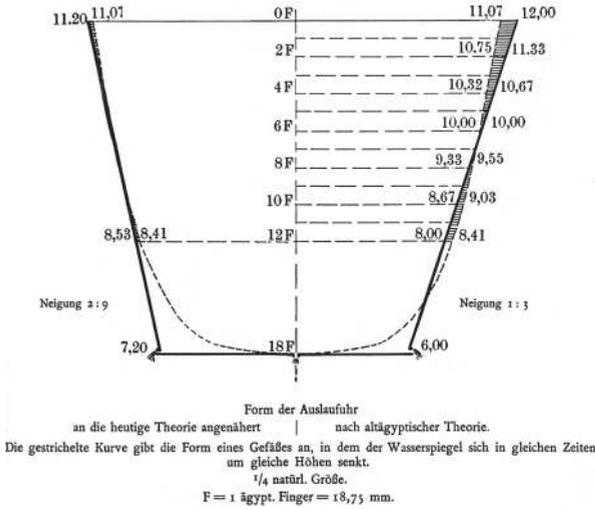


Fig. 5 Cross-section of a clepsydra and a fourth-order parabola.

Borchardt states in his summary that the display of the clock must have been wrong to an extent that should have been obvious even back then.⁴¹ However, the question remains: If this type of outflow clock did not work properly, then why were so many of them reproduced in the time of Alexander the Great and Ptolemy II? This is even more astonishing in light of the knowledge that this was the era in which the famous Greek engineer Ctesibius constructed his much more elaborate clocks at Alexandria, with far more advanced theoretical knowledge.⁴²

More than ten Hellenistic fragments of this type of outflow clock had already come to light when Borchardt wrote his book, giving the impression that he himself was quite puzzled by this obvious contradiction. Nevertheless, there can be no doubt as to their dating. Some fragments bear the names of Alexander the Great, his brother Philip Arrhidaios, and Ptolemy II. In other cases, empty cartouches point to production in a relatively short period between 320 and 246 BC, and inscriptions or find circumstances at least reveal their origins in Hellenistic times. On an overall basis, the chronological distribution of the finds is remarkable. Depictions dating from after the first appearance of the outflow clepsydra, at the time of pharaoh Amenhotep III (1379–1342 BC), have been found in four Ramesside grave chambers.⁴³ A fragment from Tanis bears the cartouche of pharaoh Necho II (610–595).⁴⁴ Nearly twenty pieces were created in the comparatively short period in the early Hellenistic times that followed. Moreover, some of these Hellenistic water clocks have been discovered outside Egypt in Turkey and Italy,

41 Borchardt 1920, 59.

42 See Schomberg 2017.

43 Barguet 1978, 52–55; Roberson 2012, 179–188.

44 Cf. Hornung, Krauss, and Warburton 2006, 494.

near Egyptian sanctuaries. In some cases, they even bear secondary Greek or Latin inscriptions, revealing their adaptation in Roman times.⁴⁵ This also means that they must have been removed from Egypt and, therefore, from the latitude for which they were originally made. It appears, therefore, that there was a deliberate acceptance of the loss of accuracy, at least in Roman times. One must take this realization into consideration before imposing modern standards on the clocks' accuracy.

Indeed, Borchardt disregards this dislocation. He even wrote, "now we must also approach the question of whether they reached this goal, whether their outflow clocks ran correctly *according to our perceptions*."⁴⁶ After having stated that the Karnak clepsydra did not work properly, however, he detected several 'Hellenistic' improvements related to the influence of Greek science and advances in theory, which according to him would have improved accuracy.⁴⁷ This served as his explanation for the revival of the Egyptian outflow clock in Hellenistic times. Since it was obvious that shape and inclination stayed the same, these improvements concerned the scales of the clocks exclusively.

Borchardt was convinced that the Hellenistic scales contained new and vital insights.⁴⁸ The lengths of the scales inside the Karnak clepsydra increase and decrease linearly, meaning that the lengths of the days/nights or measured hours did as well. This linear increase/decrease did not, however, correspond to reality: change in the lengths of days and nights is nonlinear – it happens faster around the solstices and slower around the equinoxes.⁴⁹ Since only the Hellenistic clocks would reflect such an adapted scale system, he concluded that the ancient Greeks would have been able to measure time with greater accuracy. Borchardt's evidence of this adaption, unfortunately, is based entirely on hypothetical reconstructions of scales that in fact contradict the genuine values of the preserved scales.⁵⁰ Upon closer examination, the scales of the Hellenistic clocks show linear development, just like the scales of the Karnak clepsydra.

Another of the improvements Borchardt cited, concerns the relationship between a clock's scales and the distribution of the months/length of the hours according to the contemporaneous calendar.⁵¹ He referred, in this context, not to the engraving of the hour marks on the scales in detail (the execution of these was always imprecise) but to

45 Cf. for example a fragment at the Musei Capitolini in Rome (Fig. 11; Borchardt 1920, 9 no. 12; Winter 2013, 532 no. 10) or at the British Museum in London (Inv.-no. 938; see Borchardt 1920, 8 no. 6; Winter 2013, 407).

46 Borchardt 1920, 14. Original: "jetzt müssen wir aber auch der Frage näher treten, ob sie dieses Ziel auch erreicht haben, ob ihre Auslaufuhren *nach unseren Begriffen* richtig gingen" (translation by Casey Butterfield).

47 On this point see also Hölbl 1984, 27–28.

48 Borchardt 1920, 14. "Bei der Steigerung der Skalen ist also ein Fortschritt der Theorie bemerkbar"

49 This observation was first mentioned by the Greek astronomer Kleomedes; see Bilfinger 1888, 153.

50 This discrepancy is even reflected in the data given by Borchardt himself: compare, on the one hand, his data evaluation on pages 12–13 and, on the other, his figures of the clepsydras with genuine marked scale values on plates 2 (clepsydra of Karnak) and 5 (clepsydra in the Museo Barracco).

51 Borchardt 1920, 19–21.

the question of the extent to which the length of a given month-scale corresponded to the length of the hours in exactly that month. This was due to the fundamental deficiency of the aforementioned Egyptian civil calendar: despite this calendar's advantages in comparison to the irregular lunar calendars, the lack of an intercalary day every four years inevitably had serious consequences regarding the correct display of a clock. After 120 years of missing leap-year days, the calendar would be off by a whole month. A water-clock scale for one month would display the hour length of the preceding month, and so on. In other words, the monthly display of an Egyptian clepsydra would have become irrevocably outdated after no more than 120 years.

By focusing on the distribution of the solstices and equinoxes (or the corresponding longest, shortest, and both middle scales) as representative of the entire scale system, Borchardt's analysis of the Karnak clepsydra showed that their scales did not fit the calendar at the time of Amenhotep III. Rather, they reflected the calendar of 120 years before. He saw this realization as evidence of another basic error made by the clockmakers. He categorically excluded the option that the Egyptian designers may have been aware of this fact⁵² and subsequently constructed a hitherto undocumented 'astronomic year' in order to find an explanation. R. Parker pointed to another coincidence instead:⁵³ that the established time frame might not correspond to the dating of the Karnak clepsydra but to the time of the tomb inscription by the inventor Amenemhet, from whom the scale system of the Karnak clepsydra, thus, had probably been copied.

Unfortunately, the scale system of the Karnak clepsydra does not fit the period of the inventor Amenemhet either, as revealed via an examination of the preserved scale values in contrast to the values given by Borchardt.⁵⁴ In fact, considering the scale marks that have actually been preserved, the shortest and the longest scale are to be identified with the third and ninth scale/month, respectively. These do not correspond to the fourth and tenth scales as depicted by Borchardt,⁵⁵ whose result was achieved by simply adding a hypothetical line at the top (to mark the water level at the beginning) and an imaginary twelfth point at the bottom of every scale except one – scale 10 (Fig. 6).⁵⁶ While the line

52 Borchardt 1920, 21. "ganz ausgeschlossen erscheint es aber, dass man zur Zeit Amenophis' III. eine Uhr hergestellt hat, die vor reichlich 100 Jahren einmal richtig gegangen wäre."

53 Parker 1950, 76 n. 73. "It seems to me quite safe to conclude that the scale of the Karnak clock, fitting as it does the period of the inventor, is simply another manifestation of Egyptian conservatism."

54 Compare Borchardt 1920, 12 and pl. II. While plate II reproduces the actual values, the chart on page 12 reflects an idealized version.

55 Cf. Daressy 1915, 12 fig. 5, who indicates – independ-

dently from Borchardt – the correct scales. Unfortunately, Borchardt's 'revised' values were the ones adopted following Borchardt's publication in 1920.

56 The completely preserved scales have eleven marks. Yet, according to Borchardt's concept, such a clock, which runs for twelve hours, would need twelve marks. As a consequence, he postulated that all of the scales should have had twelve marks, but with the exception of the 'shortest' scale of the tenth month, the space under the scales would not have been sufficient for another – a 12th – mark. Hence, he added one mark to the bottom of the other

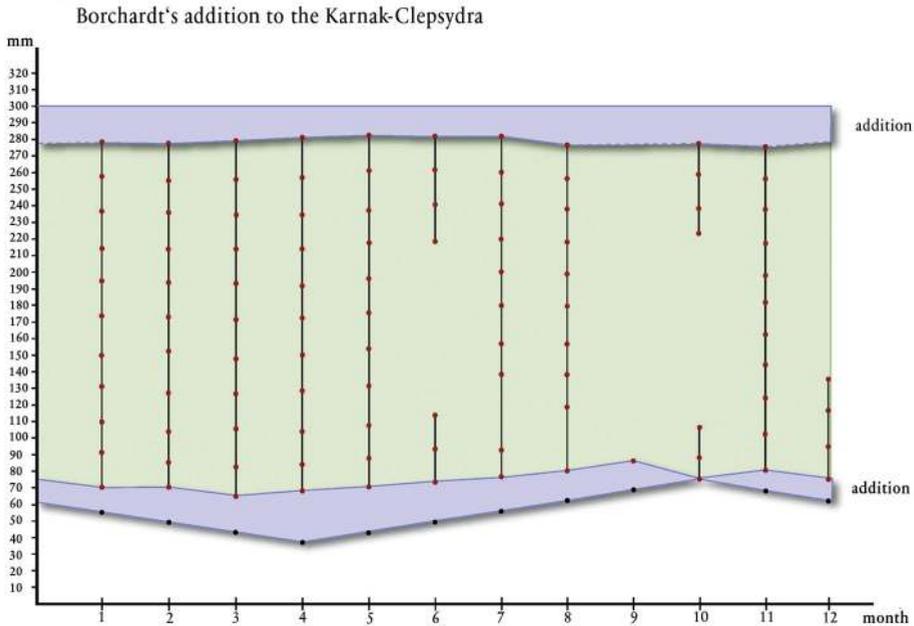


Fig. 6 Scale system of the Karnak clock with Borchardt's additions.

at the top applied to all scales to the same extent and hence had no consequences, the supplemental interval at the bottom did make a difference, since Borchardt chose the length of the added interval arbitrarily in order to restore the fourth and tenth scales as the longest/shortest scales, in contradiction to the preserved condition. According to the Egyptian civil calendar, in the years between 1700 and 1597 BC, the solstices fell in the third and the ninth month, and in this period, the scale system of the Karnak clepsydra would have been correct. Thus this clepsydra 'conserved' a calendar pattern from over 250 years prior – a pattern even older than the inventor Amenemhet himself.

By contrast, Borchardt declared that the scale systems of the Hellenistic clocks had been adapted and, therefore, accurately reflected the contemporaneous calendar situation. The problem is that most of the later specimens are only poorly preserved, making their scales too incomplete to draw such a conclusion in most cases. Borchardt, again, largely based his assumption on 'reconstructed scales.'

eleven scales and then obtained the absolute length of the scales in relation to the only complete preserved scale of the tenth month. Unfortunately, his concept was based on an incompletely preserved tenth scale and stands in contradiction to the other scales. The tenth scale has a large gap at the cen-

ter, so that only the upper four and the lower three marks are preserved. Instead of four missing marks, he assumed five – and used this assumption to justify all of his amendments; cf. Borchardt 1920, 10, 12, 15, 20–21 pl. 3.



Fig. 7 Plaster copy of the Karnak clock with reconstructed outlet.

Even the assumption of improved readability turned out to be wrong.⁵⁷ On closer examination, none of the Hellenistic improvements can be proven. Instead, a preliminary check shows that the Hellenistic water clocks seem to be faithful copies of the Karnak archetype. This calls for a new examination and estimation of the preserved material, without any hypothetical additions or reconstructions based on fixed ideas.

It was already high time, however, to reconsider Borchartd's negative judgment about the accuracy of these clocks and the modern expectations placed upon them. In a frequently overlooked article, published in 1978 in a remote journal, a German astrophysicist reported on a series of experiments with a plaster copy of the Karnak clepsydra (Fig. 7).⁵⁸ By simply filling the vessel and recording the course of the water flow, as well as the effects of cohesion and surface tension, it became apparent that, contrary to earlier assumptions, the clock displayed the time quite precisely. The clepsydra may have been an average of ten minutes too slow in the first six hours, and too fast in the second six, leaving it running around ten to twenty minutes fast after twelve hours (Fig. 8), but no other clock around 1350 BC could have revealed this lapse.⁵⁹

How could Borchartd have been so wrong? First of all, he wasn't a physicist, and in adapting Torricelli's Law to the Egyptian water clock, he made a mistake. What's more, all of his reflections on this subject were completely theoretical. The aforementioned experiments with this clock have demonstrated that cohesion, surface tension, and the

57 Borchartd 1920, 10; cf. von Mackensen 1978, 18, whose experiments with a copy of the Karnak clepsydra proved otherwise.

58 von Mackensen 1978, 16–18.

59 von Mackensen 1978, 17; similar results are provided by Cotterell, Dickson, and Kamminga 1986, 44–48.

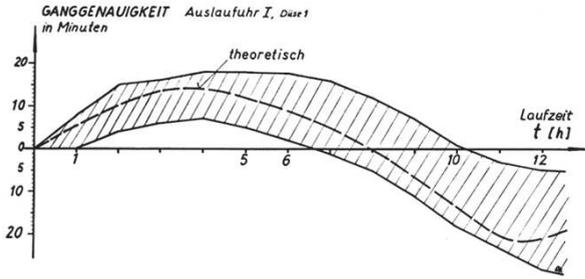


Fig. 8 Diagram showing the accuracy rate of the Karnak clock (based on 15 measurement rows).

shape of the aperture must not be neglected. In fact, they may improve the clock's proper functionality. Imposing modern standards, in terms of precision, does not help either: after twelve hours, the sun is going to rise anyway. It would not matter if the clock were ten minutes fast, since one look at the horizon would make this clear. For an Egyptian of the time, this clock would have been a precise measuring instrument. Since no other corrective instruments existed, contemporaries of the inventor Amenemhet would most likely have agreed with his assessment of the clock's accuracy.

As important as the discussion about the accuracy is, however, other aspects of these instruments have also been neglected for too long, such as their use in practice. Why was it so important for the Egyptians to have a clock available? Conveniently, the reason is written on the clepsydra itself. There to tell the time when the sun and stars are not visible, in order to make offerings at the right time.⁶⁰ Find contexts have consistently been Egyptian sanctuaries, both inside and outside of Egypt.⁶¹ On some clocks, it is mentioned that they belong to a sanctuary.⁶² These water clocks were even exported to Egyptian sanctuaries in the Roman Empire, without regard for their accuracy.⁶³ From this, it is apparent that at some point the application of this specific type of water clock or the provision of an original water clock from Egypt became more important than any precision or improved accuracy, probably because of their symbolic meaning.

This shows that the use and the development of this type of outflow clepsydra has to be put into a wider perspective. The prevailing assumption is that the invention of

60 Borchardt 1920, 8 (see London, BM, Inv.-no. 933); translation from the German by A. S.

61 Cf. Cairo, Egyptian Museum JE 37525 (Temple of Karnak); Cairo, Egyptian Museum JE 67096 (Tanis, near the great temple/Anta-temple); Turin, Museo Egizio Suppl. 8 (Rome, Iseum Campense); Rome, Museo Barracco 27 (Rome, Iseum Campense); St. Petersburg, Hermitage 2507b (Rome, Iseum Campense), Ephesus (near Serapeum); Alexandria, Greek and Roman Museum Reg. No. P. 9161 (Alexandria, Serapeum); Rom, Musei Capitolini (Rome, Regio

III near a sanctuary of Isis and Serapis).

62 Cf. St. Petersburg, Hermitage 2507a ("to offer sacrifices at the right time"); London, BM 933 ("to determine the hours [...] for the sacrifices at the right time"); Naples, Museo Nazionale 2327 (probably Temple of Osiris); Turin, Museo Egizio Suppl. 8 (originally probably a temple of the Nile god); Rome, Museo Barracco 27 (temple of Osiris); Ephesus (temple of Serapis).

63 Rouillet 1972, 145–146; Lembke 1994, 246–248; Quack 2003, 59.



Fig. 9 Roman clepsydra in the Archaeological Museum, Frankfurt.

sophisticated inflow water clocks in Hellenistic times by the Greeks in Alexandria and the subsequent innovative enhancement of such clocks in Greek and Roman antiquity exposed the apparent weakness of the old outflow clock and established much better alternatives.⁶⁴ Such an argument focuses solely on technological innovation, however, and misses a central point. The use of Egyptian clepsydras for time measurement in the Egyptian cult may have been inspired by innovation in the sixteenth century BC, but their existence in Greek and Roman times was not determined by technical feasibility. In this regard, technological progress did not make them redundant because tradition superseded innovation.

Nevertheless, the absence of this type of clock in later contexts seems to imply that the production of the outflow water clock came to an end because it could be replaced by more technologically advanced types of clocks. A closer look paints a different picture. First of all, Borchardt himself quoted a papyrus from Oxyrrhynchus that contains a partially preserved calculation of an outflow water clock.⁶⁵ Although Borchardt based his assumptions on these ancient calculations to a great extent, he could not fail to observe that the papyrus was full of mistakes, which were probably due to errors by a copyist.

A bronze vessel in the Archaeological Museum in Frankfurt provides clear evidence for the survival of this clock type.⁶⁶ Although its shape and material are different, the basic features are the same and characterize the piece as an outflow clock. Instead of

64 Cf. for example the description by Vitruvius, *De architectura* IX, 8, 2–15 (see Schomberg 2017).

65 Grenfell and Hunt 1903, no. 470; cf. Borchardt

1920, 10–12; Couchoud 1988, 25–34.

66 Stutzinger 2001, 5–12, 22–46.



Fig. 10 Fragment of a Roman clepsydra from Vindolanda.



Fig. 11 Fragment of an Egyptian clepsydra in the Musei Capitolini in Rome.

a truncated cone, it has the shape of a bowl, with a specific inclination to meet the flow requirements (Fig. 9). Inscriptions on the rim give the names of the months, the equinoxes, the solstices, the calends, the nones, and the ides. Drilled into the rim are 368 holes for the days, and two holes can be found at the bottom: a large one, with traces of a different material, and a very small one made of gold⁶⁷ that served as the outflow aperture. The time was indicated by the sinking water level against twelve scales on the inside. Unfortunately, the accuracy of the clock has not yet been examined. Another inscription on the outside reveals that it was dedicated to a Gallo-Roman sanctuary. This Roman clepsydra can be dated to the second century AD for epigraphic reasons.

Recently, another fragment has come to light in a remote area of the Roman Empire. In the fort of Vindolanda at Hadrian's Wall, a small bronze stripe was discovered in the remains of a granary dating to the second/third century AD (Fig. 10). The inscriptions on this stripe have led to its interpretation as a calendar or as part of a bronze disc from an anaphoric clock.⁶⁸ Seen in comparison to the rim of the clepsydra in Frankfurt, however, it proves to be a fragment of another Roman outflow clock. The origin of these Roman pieces is still recognizable, as a look at a fragment of an Egyptian forerunner in the Musei Capitolini at Rome shows (Fig. 11).⁶⁹ This type of clock was obviously such a success that even in the face of more advanced devices, and despite the end of antiquity, it continued to be used. Even a medieval Arabic manuscript in the British Library contains a description of how to build such an outflow clock (Fig. 12–13),⁷⁰ which attests to a much more persistent tradition of this type of clock than previously thought.



Fig. 12 Page 13 of an Arabic manuscript, in which various technological texts are detailed (691/1292 AD).



Fig. 13 Page 10 of an Arabic manuscript, in which various technological texts are detailed (691/1292 AD).

As stated at the beginning of this paper, the study of the use of water clocks to measure time in Greek and Roman antiquity suffers from one major problem: until now, such investigations have relied almost entirely on written sources. Sophisticated devices like the Ctesibius clock left no traces and survived only in descriptions. Yet, as we have seen, nearly thirty outflow water clocks ranging from 1400 BC to AD 300 have been preserved in various states of fragmentation. An inventor’s description, as well as a Greek and an Arabic manual, provide insight into their construction. Even pictorial representations of this instrument in certain contexts are available. Unfortunately, the material

67 This aspect can be attributed to technological progress with reference to Vitruvius. As he reported, it was the Greek engineer Ctesibius of Alexandria who first created an aperture made of gold or a perforated gem for a water clock; see Vitruvius IX 8, 5; cf. Rowland 1999, 116.
 68 M. Lewis 2009, 12–17; Birth 2014, 395–411; Meyer 2014, 109–115.
 69 Borchardt 1920, 9; Winter 2013, 532.

70 The manual is preserved in two Arabic manuscripts: one in the British Library in London (Ms. Or 14270) which is available online, see http://qdl.qa/en/archive/81055/vdc_100023698323.oxo00001 (visited on 23/05/2018), dated 12th October 1292, and the other in the Bibliothèque nationale de France in Paris (Ms. 2468); cf. Wiedemann and Hauser 1915, 25–29.

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Illustration credits

1 Young 1939, 282 Fig. 4. 2 Neugebauer and Parker 1969, Pl. 2. 3 Desroches-Noblecourt 1976, 141. 4 Borchardt 1920, Pl. 2. 5 Borchardt 1920, 16 Fig. 3. 6 Anette Schomberg. 7 Von Mackensen 1978, Fig. 2. 8 Von Mackensen 1978, Fig. 7. 9 Stutzinger 2001, Fig. 2. 10 Birth 2014 Fig. 1. 11 Anette Schomberg. 12 San'at al-zāmir صنعَة الزامر Apollonius the carpenter and geometer أبلونيوس النجار الهندسي [20r] (13/15), British Library: Oriental Manuscripts, Or 14270, ff 14r-21r, in

Qatar Digital Library <https://www.qdl.qa/archive/81055/vdc_100023867439.0x00002e> [accessed 7 June 2018]. 13 San'at al-zāmir صنعَة الزامر Apollonius the carpenter and geometer أبلونيوس النجار الهندسي [18v] (10/15), British Library: Oriental Manuscripts, Or 14270, ff 14r-21r, in Qatar Digital Library <https://www.qdl.qa/archive/81055/vdc_100023867439.0x00002b> [accessed 7 June 2018]. 14 Anette Schomberg (Berlin Waterclock Project).

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