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Tunnel and ventilation design of the Eupalinos' aqueduct in Samos, Greece

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Polycrates' extended reign and a recently discovered extension of the distribution sector of the aqueduct prompted this review of the design and tunnelling of the Eupalinos' aqueduct. Both aqueducts, the Archaic and Roman, cross an affluent area of the upper city, located less than 10 m below the level of the water source, a condition critical for the aqueduct's design. The tunnel's detour from its initial axis and the function of the tunnel as an integrated element of the city's defensive works are also discussed. A key consideration of this review is the ventilation of the lengthiest blind segments of the Eupalinos' tunnel, given that natural ventilation in a blind gallery is generally not effective beyond about 50 m. Considering the historical evolution of ventilation in underground works, it is proposed here that a ventilation circuit was maintained along the tunnel through an auxiliary gallery dug simultaneously a few meters below the tunnel.

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1. Introduction

The Eupalinian aqueduct has been extensively studied and celebrated as an exceptional engineering project of the sixth century BC, as well as a physical demonstration of the mathematical problem presented by Hero of Alexandria in the first century AD.[1] Famous for its 1 km-long tunnel which pierces the Kastro Hill, between the Ayiades spring at 52.36 m above mean sea level (amsl) and the city of Samos, the aqueduct is composed of a series of three composite parts: i) the supply sector (I), ii) the tunnel segments II and III and the underlying gallery, and iii) the distribution segments IV and V (Figure 1). The supply sector, outside

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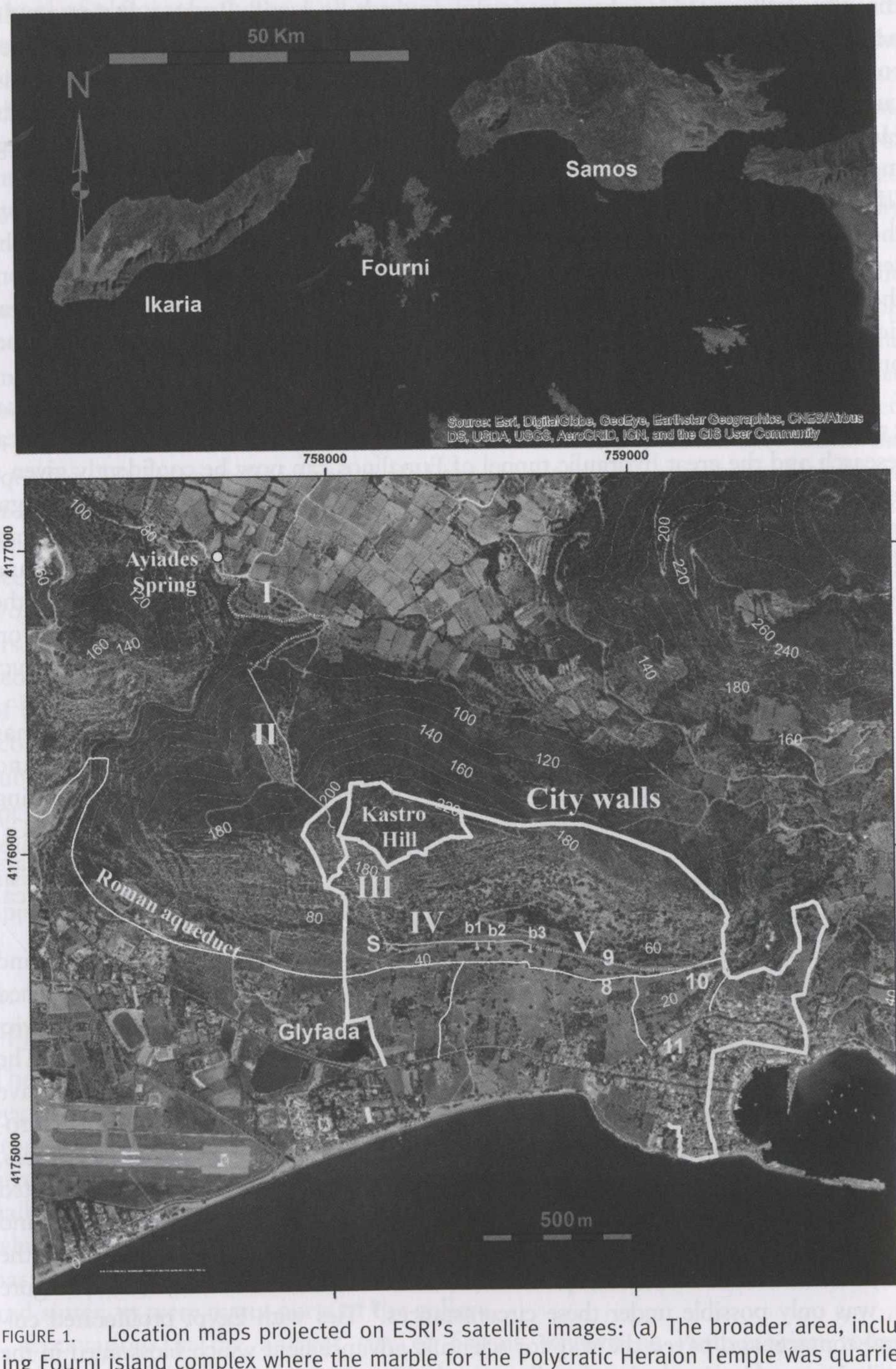

FIGURE 1. Location maps projected on ESRI's satellite images: (a) The broader area, including Fourni island complex where the marble for the Polycratic Heraion Temple was quarried. (b) The Eupalinian and the Roman aqueducts and the walls of the ancient city of Samos, in Greek coordinates (EGSA).

the city walls, carries water from the copious and still flowing spring to the northern mouth of the tunnel. The tunnel was laid out along a carefully planned route.[2] It was originally designed straight and horizontal but for reasons discussed below there was a deviation from alignment corrected afterwards. However, at all costs it was kept horizontal for an easier meeting of the two segments. It is composed by construction of two independently dug segments II and III, 1.8 × 1.8 m in section. After a local deviation of the northern branch from the horizontal plane of the mouths, the tunnel returned to the original level. The segments started from both mouths and crossed each other about 612 m from the north and 424 m from the south outlet point. As confirmed by recent excavation reports, the distribution sector inside the city walls, extends from the tunnel outlet to the centre of the ancient city.

The tunnelling works began, according to all evidence available, as early as *ca.* 550 BC, a view that has recently been supported by Aideen Carty's historical research and the great hydraulic tunnel of Eupalinos can now be confidently given a *terminus ante quem* of *ca* 540 BC.[3] The chronological extent of Polycrates' reign, however, was traditionally dated to between 533–522 BC, leading Kienast to state that 'the frequent assertion that Polycrates sought an architect for an aqueduct and invited Eupalinos from Megara is not tenable'.[4] It is also commonly held that the aqueduct of Eupalinos and the harbour installations presuppose the existence of fortification walls encircling the city.[5] The city's walls, the harbour, and the aqueduct are considered to belong to a unique plan of public works attributed to Polycrates.

The traditional chronological date for Polycrates' accession, *ca.* 533 BC, has recently been seriously challenged by a range of scholars. Touratsoglou and Tsakos consider an earlier date of 538 BC for the tyranny of Polycrates aligning with the peak of Samos's heyday and the beginning of its decline in 522 BC;[6] while Carty argued convincingly for Polycrates' accession one or two years before the fall of Sardis in 547 BC.[7] This revision removes any chronological obstacles in linking the aqueduct with the reign of Polycrates.

Samos under Polycrates' rule has been described as the greatest naval power and mercantile hub of the Archaic age. This source of power and thalassocracy stemmed from an alliance with the Egyptian pharaoh Amasis, following Polycrates' naval victory over a combined Milesian and Lesbian force, both pro-Persians. The Eupalinian aqueduct, and the other great civic works in Samos, would not have been possible without Polycrates' Archaic thalassocracy, a powerbase which provided the context for the contribution of seafarers, scientists, architects, engineers, and masons. This collaborative context enabled great civic works of unprecedented scale which both benefited from, yet at the same time also fuelled, scientific and technological progress. For example, the introduction of marble columns to the Polycratic Heraion of Samos, quarried in the islands of Fourni near Ikaria (Figure 1), was only possible under these circumstances.[8] Ties with Egypt proliferated cultural contacts and paved the way for scientific advancement which blossomed in the fertile Ionian zeitgeist, perhaps at the expense of mythological belief.

Thus, the date for the construction of the aqueduct falls under the floruit of Samos, during a period of Ionian scientific and philosophical enlightenment. Thales, Anaximander and Anaximenes are usually grouped under the Milesian school of philosophy, because all three philosophers lived in Miletus in the seventh and sixth centuries BC. Pythagoras' mathematical works are also guessed in the design of the aqueduct.[9] The contribution of Ionian philosophers to science is currently recognized with the recently coined expression Ionian Enchantment. According to Edward Wilson, Ionian Enchantment relates to a belief in the unity of the sciences presenting 'a conviction that the world is orderly and can be explained by a small number of natural laws'.[10] The concept of Enchantment is steadily becoming more sophisticated and has dominated scientific thought ever since.

In this article, emphasis is given to a series of interrelated issues pertaining to the famous aqueduct, including the reasoning behind the initial tunnel design, the following deviation from the initial alignment and possible reasons for this, and the important issue of ventilation while digging the blind tunnel segments. These themes are all considered in the context of new archaeological evidence which is integrated in the analysis. The new archaeological evidence for the intraurban network of the aqueduct, highlighting the importance of the ancient upper city, are considered here in the light of the newly proposed chronologies for Polycrates' reign. The description of the overall aqueduct system is kept to a minimum here as it has already been published in great detail by the German Archaeological Institute, mainly in the works of Kienast, but also is addressed in recent publications by independent scholars (Lyberis et al.; Zambas et al; Zambas).[11] Instead, emphasis is given on the archaeological evidence from recently published excavations on the distribution sector of the aqueduct and the importance of the ancient upper city. In short, within this scope, the objectives of this article are the investigation of a series of interrelated subjects including the implications of the new archaeological evidence, the reasoning for the initial tunnel design, the deviation from the initial alignment and the possible reasons, and the important task of ventilation while digging the blind tunnel segments. The ventilation issue is evaluated based on a historical study of the methods applied since antiquity until the first alpine tunnels in Europe.

2. New evidence for the distribution sector and settlement in the upper city

The distribution sector was considered by Kienast to extend along the City Segment marked as IV in Figure 1, a course of about 620 m in length extending from the south portal, S, (where 'portal' refers to the inlet or outlet point of any given tunnel), to the supposed by Kienast terminal point b3.[12] At this point, the gallery supplied water to a short crosscut, heading southwards, at the end of which the foundation of a basin, b3, was found in situ. Similar crosscuts and basins are assumed at points b1 and b2, but they were found blocked by mud and sinter, as were many parts of the gallery.

Excavations in the ancient city of Samos, known as Pythagoreion today, recently revealed the continuation of the Eupalinos' aqueduct in the upper city beyond point b3. The distribution sector continues eastwards, along segment V, towards the centre of the ancient city, at least up to Point 11. The excavations for the New Gymnasium school building, originally planned at Site 8 in Figure 1, yielded significant Archaic and Hellenistic architectural remains and the school was finally relocated to Site 10, where, again, Archaic hydraulic installations were discovered. The project design and other aspects of the aqueduct's construction can be better understood from these new findings.

In 1983–1984 at Site 8, a few metres below and parallel to the public road, a Hellenistic villa was excavated revealing marvellous mosaics of excellent artistic quality dated in the second quarter of the second century BC,[13] while an adjacent Archaic fountain house and a section of the Archaic aqueduct were located at Site 9. A barrel-vaulted tile roof was added to the large Archaic fountain-house at a later stage demonstrating its longevity of function. North of the buildings, a pile of numerous Π-shaped pipes was found stacked at the ground surface. Two shafts were disclosed nearby, at Site 9, connected to a section of a gallery, 2.16 m high and 0.55 m to 0.60 m wide, considered to be at the extension of the city segment IV. The natural rock in the gallery floor was found at an elevation of *ca.* 43 m amsl, about 9 m below the spring.[14]

Further continuation of the distribution sector was excavated at Site 10 (marked in Figure 1) of the new Gymnasium building where it ran in front of the eastern side of the middle school block following a northwest-southeast axis for a length of 7.6 m; it then turned smoothly from north to south, for an excavated length of 19 m, veering towards the centre of the ancient city. Although reported as an underground gallery, it is a covered channel in my opinion cut from the surface and covered by corbelled stone plates. The vertical walls are also lined with masonry, the channel is 1.8 m high and contains a semi-circular ceramic pipe at the bottom. It is suggested by the excavator, Loupou, that the original channel is Archaic and that it terminates at a cistern 250 m away.[15] Indeed, a complex of at least two underground cisterns was excavated at Site 11 (marked in Figure 1) a few years earlier.[16]

The distribution gallery from the south portal to the Archaic fountain at the point 8 is dug underground, 0.6 m wide and remarkably high, 2.2 to 2.6 m. The trace of the city gallery at the junction below the south portal at Point S, is S-shaped, an indication that the gallery was dug from both sides towards Point S.[17]

Meticulous excavations in the lower city of Samos revealed archaeological remains of successive periods, from the Archaic to the Roman and Byzantine times. Frequent hydraulic structures including cisterns and terracotta water pipes as well as drainage conduits indicate a well-organized water supply and drainage network operating over many centuries.[18]

The source of the water for the centre of the ancient city cannot be securely identified and could either be the Eupalinian or the Roman aqueduct. However, the excavated Hellenistic pipeline at the Panagitsa near Glyfada (Figure 1) is reasonably thought to have been fed by the Eupalinian aqueduct.[19]

3. Discussion

3.1. Considerations on the Eupalinian tunnel design

The landscape in the upper city has not changed significantly since antiquity, as indicated by both excavations and well-preserved remains of ancient retaining walls, although the alluvial cover might be locally thicker. Excavations indicate that the ancient settlement extended close to the western branch of the Archaic wall,[20] while, to the north, the upper city extended up to the modern road leading to the south portal of the tunnel, or as described by Giannouli, up to the rocky limestone outcrop with sculptured niches of Cybele.[21] The Archaic fountain-house, the Hellenistic and Roman villas and Giannouli's general reference to a palatial building, points to an affluent area in the upper city which might explain why the route of both aqueducts, the Archaic and the Roman, pass through the area. The natural advantage of the area might be its good view of the harbour, which offered an early warning against frequent attacks, and the convenience of organizing defence or escape through the tunnel of the aqueduct. It should be noted here that the Roman aqueduct route (marked in Figure 1) was based on the careful mapping and description by Dimitriou[22].

3.1.1. The initial design of the civic water supply system

We deduce that the design of the whole project was based on fundamental prerequisites, including securing the water supply of the upper city, achieving the shortest possible completion time for the project, and integrating the aqueduct within the city's defence walls. These conditions, together with the challenging elevation of the upper city and securing the shortest possible aqueduct route from the spring up to the south portal, required the design of a tunnel to be dug simultaneously from both ends.

The gradient of the supply sector was laid out with extreme care and adhered closely to the lower gradient range for the desired water rate of *ca.* 400 m^3 daily. The spring rests at 52.36 m amsl while the first recorded pipe, 17 m from the spring, sits at 52.89 m amsl; meaning that the water level in the cistern was at least 0.6 m higher than the spring. The floor of the gallery, at the crossing with the tunnel, sits at 51.25 m amsl. Four other intermediate points, where the bottom of the trench was exposed, lie exactly on the connecting line defined by the above end points. This well-designed course extended over a length of 870 m with an elevation difference of about only 1.75 m and a gradient of 2 m/km.[23] The elevation of the floor of the water gallery below the southern portal, at Point S (marked in Figure 1), is 47.66 m amsl, that is only 4.7 m below the spring with an average gradient 2.4 m/km, difficult to achieve without the tunnel.

An alternative aqueduct around the Kastro Hill would have been possible, either as an extension of the supply sector in the shafts-and-gallery tunnelling technique or as a covered channel. It would then extend outside the city walls, west of the hill in the zone running close to the 60 m contour and the existing Roman aqueduct. In this alternative scenario, the aqueduct route would extend for a kilometre longer, and the hydraulic gradient would be less than 1.5 m/km, which is marginally low for the gravity flow in a slalom channel. Gradients of Roman aqueducts varied between 1.5 and 3.0 m/km;[24] the Eupalinos' aqueduct, constructed long before them, complied with this range of gradient. However, the Roman aqueduct at Side in Turkey is about 30 km long with a fall of only

36 m, but it is composed of a sequence of many aqueduct bridges and tunnels constructed using the shafts-and-gallery technique.[25] As stated in a literary but accurate description by Alfred Friendly 'from its source to the entrance in the second storey of the great city wall of Side, the water channel falls about 30 m, making the ratio of its drop about 1/1000'.[26]

In addition to the hydraulic considerations, a decisive advantage in incorporating the tunnel system was, in my opinion, that the tunnel itself was intended *a priori* as part of the city's defence and this duality of function facilitated the acquisition of the required resources while safeguarding the city. It is plausible to envisage that the tunnel had been designed to operate as a potential 'sally port' or an escape way. This dual purpose for the tunnel would not be unusual in the Polycratic context of extended tyranny and accrued wealth. It is notable that an escape route out of the city through a secret passage leading from the citadel to the sea is mentioned by Herodotus (Herodotus 3, chapters 145 and 146).

The design and excavation of the water gallery below the tunnel is a critical and complicated topic. Kienast finds it strange that the transition from the supply sector to the water gallery occurs at a depth of about 4 m below the tunnel floor, 'though with proper planning it could have started at the floor level of the tunnel, which is today higher than the level of the spring'.[27] His explanation is that during the excavation of the tunnel, the spring shifted about 4 m lower, and this necessitated lowering the pipeline gallery accordingly. In my opinion, the gallery was intentionally designed from the beginning at this depth to serve the required ventilation circuit, a critical point discussed below.

3.1.2. Design changes and the angled detour of the tunnel

Despite the initial design of a straight horizontal tunnel, a detour was undertaken for unknown reasons. An enigmatic departure from the initial alignment is marked by an angled detour along the northern branch of the tunnel, coinciding with a smooth rise in the floor up to 2 m. Points 23, 26, 28 and 30 (marked in Figure 2) are numbered as on Kienast's plans for ease of comparison. Before examining different interpretations for the route deviation, the relevant data will first be summarized. Near the beginning of the detour, at Point 26, sizable stalactites occur which presented an insurmountable barrier in the 19th century.

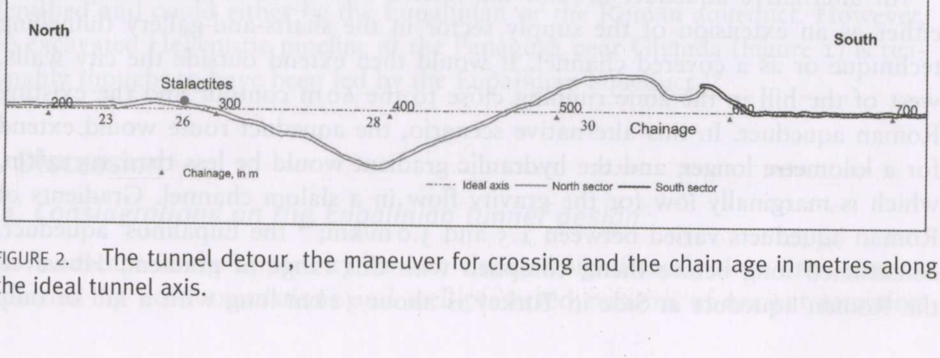

FIGURE 2. The tunnel detour, the maneuver for crossing and the chain age in metres along the ideal tunnel axis.

Opening a passageway in modern works by means of an electric hammer proved a laborious task.[28] The stalactites, marked in Figure 2, are considered primary, in the sense that they existed before tunnelling in natural caves, as indicated by the fact they extend beyond the tunnel floor.

From Point 28 the route is corrected along both planes, elevation and plan, firstly returning to the initial floor elevation and then the heading is modified following an impressive maneuver for the successful crossing. It is noteworthy that along the first section of the detour, between Points 23 and 28, and for a length of 135 m, visibility is hindered beyond a couple of metres, due to its slalom route. In contrast, along the second section of the detour, between Points 28 and 30, the route follows a straight course. It is perhaps relevant that along the 135 m-long slalom section of the tunnel, where the tunnel section is rectangular, although the rock is fractured, no collapse was recorded.[29]

3.1.3. Reasons for the detour

Kienast attributed the detour to collapsing rocks, because of which 'Eupalinos seems to have abandoned the original straight line in an attempt to reach safe rocks'.[30] In addition, about 200 m from the north portal the tunnel is crossed by 'a seam of water' and the floor of the tunnel rises smoothly in order, according to Kienast, to keep water away from the excavation face[31]. At the point where the seam of water ends, the floor of the tunnel returns to its original level.

The initial straight section of the tunnel, however, was driven successfully through a more friable collapsing rock formation, while no collapse is recorded along the slalom detour of rectangular tunnel section. In addition, the notion of a water-bearing 'seam', which can be avoided by rising the tunnel floor by 2 m, does not correlate with the local geological setting of strongly dipping layers and vertical water flow 50 m amsl, as attested by the stalactite columns.

As indicated in Figure 3, compiled from evidence in the literature, groundwater flow and rock caving are common all along the tunnel.[32] Rock collapses are mainly due to tectonic rock faulting and fracturing, facilitated also by groundwater flow, which often result in «chimneys» of pointed roof collapses. Even in the zones of Archaic lining near the north portal (Figure 4 by G. Koulouriotis[33]), roof collapses were recorded and repaired recently, but the tunnel route generally maintained a straight course in zones prone to collapse.[34] In the Eupalinian tunnel

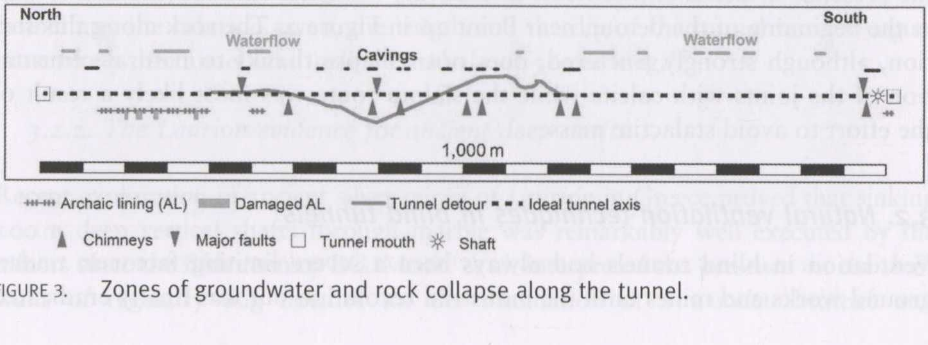

FIGURE 3. Zones of groundwater and rock collapse along the tunnel.

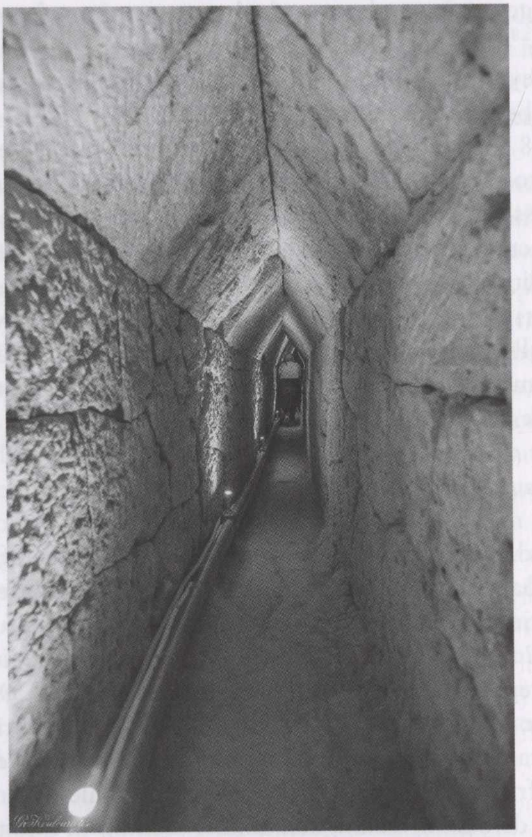

FIGURE 4. Archaic lining at the northern end of the tunnel, traced in Figure 3, in photograph by G. Koulouriotis.

secondary stalactites -created after the tunnel construction- abound in the zones of vertical groundwater flow, however, drainage through a channel at the bottom of the gallery would not be problematic. It seems that the stalactites were formed during the Holocene in the last ten thousand years, because earlier, during the glacial period, the rocks were submerged in the sea. The caves have a longer history of karstification since the tectonic uplift of the island.

In my opinion, the detour was necessitated by crossing a cave as indicated by the presence of dense and difficult to excavate stalactite columns, similar to that at the beginning of the detour, near Point 26 in Figure 2. The rock along this section, although strongly fractured, does not collapse thanks to natural cementation of the joints with calcite while the slalom route was most likely a result of the effort to avoid stalactite masses.

3.2. Natural ventilation techniques in blind tunnels

Ventilation in blind tunnels had always been a severe limiting factor in underground works and mines until the industrial revolution but was finally eradicated with the introduction of mechanical fans in the second half of the nineteenth century in Alpine tunnels. There is no direct evidence regarding the ventilation methods used during the excavation of the Eupalinian tunnel, and it is hoped that a review of some ancient aqueducts and medieval or later mines will benefit this investigation of potential applications for the Eupalinian tunnel.

3.2.1. Natural ventilation in ancient hydraulic blind tunnels

The Hellenistic aqueduct for the city of Gadara, Jordan, about 30 km long, built mainly in the shafts-and-gallery tunnelling technique, included a *ca.* 600 m long blind tunnel. This section crosses the watershed range at a depth of up to 72 m below ground-level and that makes the construction of shafts a difficult task, although deeper shafts are known and were commonly dug at the Classical Laurion mines in Greece. Along the Gadara aqueduct, a horizontal auxiliary gallery was dug a few metres laterally and higher than the blind tunnel, which was connected to the aqueduct at intervals by means of inclined shafts.[35] In a later construction phase, the Roman transregional aqueduct, the Qanāt Fir'aun, incorporated this supply system at the watershed. I believe that this coupling of auxiliary gallery and the main tunnel was designed for maintaining a ventilation circuit with two access openings on the ground surface set at different elevations.

Another blind tunnel dug almost horizontally by the counter-excavation technique, meaning from both ends through a hill along the Roman aqueduct of Knossos in Crete. The 1150 m long tunnel was built in the Roman period to carry water to Knossos from a spring about 10 km away. The tunnel was cleaned in the first half of the nineteenth century for reuse. There is no indication for the ventilation system applied during the original Roman tunnelling project, it is known however that during the cleaning works in the nineteenth century workers died of suffocation.[36] There must have been, therefore, a ventilation structure or system in antiquity, unknown currently, which in combination with the method and accuracy of breakthrough compose an interesting area for further investigation. I guess that a second auxiliary tunnel was dug as in Gadara.

The famous Roman tunnel of Saldae in Algeria was also dug from both ends, most likely blind, by the librator, leveller or surveyor in modern terminology, Nonius Datus in 137 AD who was transferred elsewhere and delivered his plans to his successor. The connection of the two sectors failed and Nonius Datus was recalled to successfully complete the work after twenty years. The error in the tunnelling, the solution given, the length and the dip of the tunnel remain vague; most likely the tunnel was inclined and about 560 m long.[37]

3.2.2. The Laurion evidence for ancient deep shafts

Recent exploration of ancient silver mines of Laurion in Greece proved that sinking 100 m deep vertical shafts through marble was remarkably well executed by the miners since the fifth century BC. Morin et al. interpreted the presence on the shaft walls of regularly dug notches for the installation of a wooden brattice and partitioning the shafts into two ducts of unequal cross-section. They further suggested that several kinds of asymmetry could have been exploited for ventilation, such as differences in pressure, temperature, or humidity. Another solution in Laurion for the ventilation of deep shafts was the construction of an oblique gallery, joined a few metres below the surface, like some 16th-17th century mining structures, where a brazier was lowered a short distance down the shaft to heat the air.[38]

As indicated in Figure 5 many vertical shafts in Laurion have a regularly twisted rectangular cross section from top to bottom, considered to enhance natural ventilation. [39]

3.2.3. Natural ventilation in old mines

Digging the water gallery from the tunnel floor, suggested by Kienast as proper planning at the Eupalinos' aqueduct, would imply that the system of the tunnel and water gallery was dug 'blind', with a single communication point to the ground for a length of about 400 m at the south and 600 m at the north segment.[40] However, old mining experience shows that natural ventilation is maintained only over a length of some tens of metres in the case of a blind gallery and that a second portal is required in longer networks. This experience also underpins shafts distance in shafts-and-gallery tunnels which varies between 20 and 80 m; it is also embodied in many governmental regulations on mining safety which establish a maximum length of 30 m in blind heading.[41] The

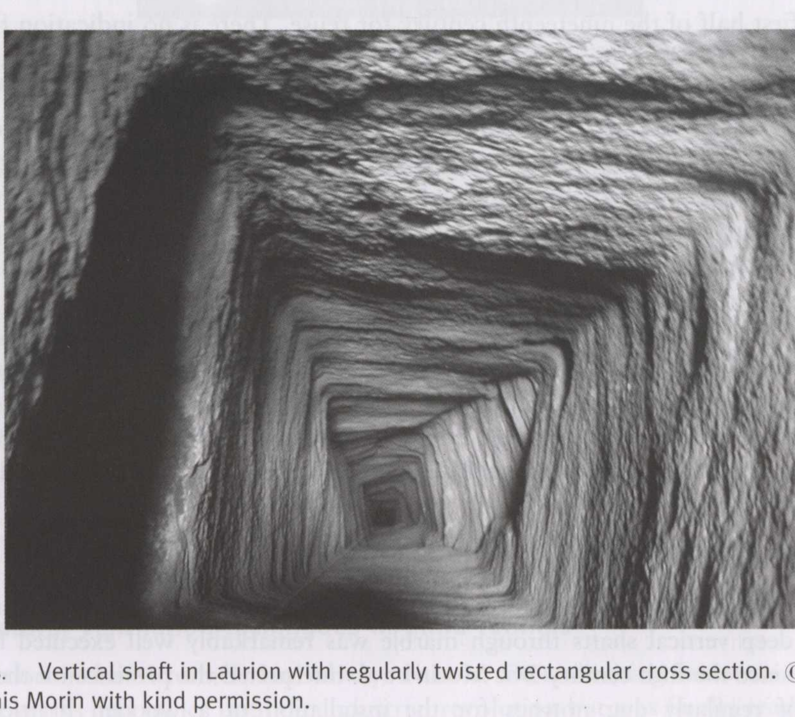

FIGURE 5. Vertical shaft in Laurion with regularly twisted rectangular cross section. © Photo by Denis Morin with kind permission.

recommendation is evident in empirical formulations which determine that in auxiliary ventilation systems the distance from the ventilation outlet to the development blind heading should be in the range of 5-21 m.[42]

For more than 30 years the Speleological Association for the Study and Preservation of Old Mines (ASEPAM) worked for the preservation and study of the mining, geological and mineralogical heritage of the Silver Valley in Alsace, East France. They opened to the Public silver mines of the Renaissance and studied the ventilation systems and mining techniques with intriguing results. Almost all the mines in the St-Louis vein have a ventilation shaft in communication with the main gallery. Beyond the ventilation shaft, traces of a brattice of boards appear in the gallery in order to create at the roof a false ceiling and above it a 'ventilation duct' about 0.1 to 1 m high (Figure 6). Finally, the brattice was sealed with clay placed on top of the boards. The ventilation shaft is located less than 50 m from the gallery portal and varies in depth from a few to nearly 20 m.[43]

The driving force behind natural ventilation is of a thermal nature, associated with the temperature difference between the atmospheric air at the portal and the rock temperature at the end of the gallery. Florsch et al. presented a physical analysis of air circulation in a horizontal blind gallery based on air velocity and temperature measurements.[44] They estimated the distance of about 50 m beyond which natural ventilation no longer works. They also applied a theoretical analysis which yielded the following equation for the air velocity, V, as a function of the temperatures outside (Tout) and at the end of the gallery (Tend), the gallery height, H, and the distance from the gallery portal (x), g being the acceleration of gravity:

$$V = \sqrt{\frac{Tout - Tend}{Tend} \frac{gH}{2} e^{\frac{-x}{4H}}}$$

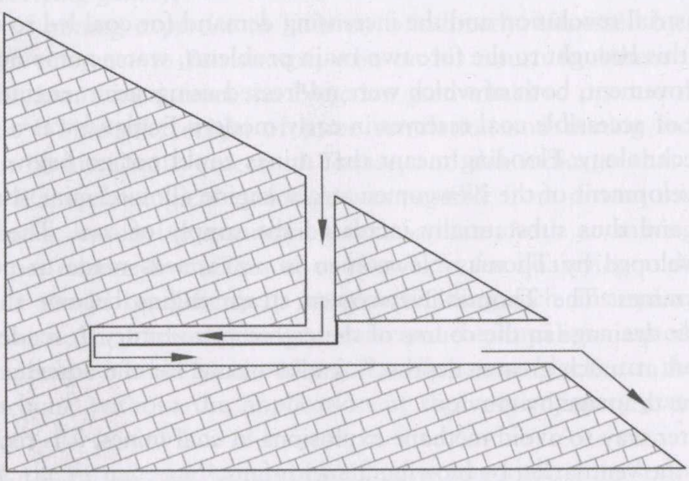

FIGURE 6. Schematic design of the 'false ceiling' ventilation system where the gallery is progressively separated in two horizontal sections by means of a brattice, the upper one of which is connected to a shaft.

The equation is valid for two-dimensional modeling, at least for galleries between 50 and 80 cm wide, and shows that the velocity would be greater for wider galleries. Both, the equation and velocity measurements confirm that beyond 40 to 50 m the air stagnates, oxygen is not replenished, and respired carbon dioxide is not removed. In the common case where the air is warmer than the rock walls of the tunnel it flows along a zone near the ceiling, comes to thermal equilibrium and returns along the floor, so it does not penetrate deeper.[45] This is one of the reasons why shafts are dug in the aqueducts along the gallery in the shafts-and-gallery tunnelling technique. It is a solution of necessity for the ventilation and extraction of the excavated material and is not related to the Persian qanats at all. There is no doubt about this in Samos, where supply and distribution branches predate Persian influence in the region.

Natural ventilation circuits in old mines were created through two or more openings at the surface at different elevations, one of which most commonly was a ventilation shaft. Surface winds and falling water may also enhance natural ventilation. The temperature of groundwater may alter the temperature of the air and this can influence the natural draft. The velocity of waterfall also transmits energy which, through the resistance of the air to its passage, exerts pressure in the flow direction. Moisture can also play an important role in modifying heat exchange in the mine by condensation or evaporation. Statistical data from mines in Alsace dated in the renaissance indicate that by means of false ceiling natural ventilation can reach up to 200 m.

3.2.4. *Ventilation in coal mines and tunnels before the introduction of fans*

Ventilation experience from old mines was considered in coal mines and the first modern tunnels in the middle of the nineteenth century. Coal was the vital fuel of the industrial revolution and the increasing demand for coal led to deeper coal mines and this brought to the fore two main problems, water pumping and ventilation improvement, both of which were addressed using steam engines.

The size of accessible coal reserves in early modern England was a function of drainage technology. Flooding meant that mines could not go below 50 metres, but the development of the Newcomen steam engine allowed mine shafts to be a lot deeper and thus substantially increased the supply of coal. The first steam engine, developed by Thomas Newcomen in 1712, was made to pump water from coal mines. The Thomas Newcomen steam engine become the standard means of pit drainage in the course of the eighteenth century. It made it possible to mine coal at much greater depths;[46] it also meant for the aqueducts an alternative to the drainage by gravity.

As a better way to avoid methane explosions in coal mines, it is recommended to increase the ventilation by blowing air with fans.[47]

The well-known means of mine ventilation in the first half of the 19th century were the heating of the air at the outlet, the suction of air by machines with reciprocating pistons and the blowing of air by fans.[48]

To improve ventilation in various coal mines, piston suction machines were applied, which were first tested in Belgium in 1830 to replace ventilation fireplaces. The hearth that the machine replaced was usually installed at the bottom a well and ended on the surface in a chimney 25–30 m high. The machine consisted of two prismatic wooden cases, in which pistons of square cross-section, side 2.40 m, moved in a stroke of 1.60 m with 19 reciprocations per minute. Rotary fans are also described.[49]

The Semmering Railway in Austria was the first Alpine railway (1848-1854) 85 m below the summit of the pass through a 1430 m long tunnel. Ventilation was provided by ten shafts and excavation faces progressed in both directions from the shafts, so that the blind sections were less than 70 m long in average.[50]

Alternatively, the furnace-and-chimney method has been used, to a limited extent, to ventilate tunnels during construction (Figure 7). In this method, the air is heated near the bottom of the shaft or chimney, thus producing a steady current which draws the heated air through the shaft or chimney and causes fresh air to flow in at the portal towards the working face. The furnace and chimney method gave good results at the Moorhouse Tunnel in New Zealand in 1865. It was also tested in the Mont Cenis Alpine tunnel before the application of fans.[51]

3.3. Ventilation in the Eupalinos tunnel

Hoping to identify techniques applicable to the Eupalinos tunnel, the preceding review presented the fundamental stages of the pre-industrial evolution of ventilation methods and demonstrated how old ideas had evolved in subsequent applications. Indeed, the Gadara aqueduct in Jordan coped with ventilation problems in the main gallery by the simultaneous construction of an auxiliary connected gallery, a solution similar, in my opinion, to the system of the Eupalinos tunnel and the underlying gallery.

Transfer of mining expertise to Laurion is indirectly witnessed by Herodotus (1.64.1) with reference to Peisistratos, who on his return to Athens in 546 BC, brought with him miners from the Paggaion gold mines to operate the Laurion silver mines.[52] Thus, the origin of some ventilation and mining techniques in Laurion can be historically traced to Thrace, and this indicates that in the first millennium BC, technological exchange was possible from distant mining areas. It is therefore a reasonable assumption that Samians, with no mining tradition, would also use experts from Thrace, or elsewhere, for quarrying and tunnelling. Otherwise, it would be difficult to imagine building such unsurpassable works like the Heraion, the harbour, the city walls and the Eupalinos aqueduct as well as quarrying either marble for the Heraion or limestone blocks for the city walls and the harbour, without the application of the contemporary state-of-the-art technology.

Similarly, the furnace-and-chimney method is essentially a 19th century modernization of the false ceiling method used in the old mines in Alsace, indicating the adaptation of older technology to new applications. In the tunnel of the Semmering railway, they reached a blind section length of 70 m and dug shafts

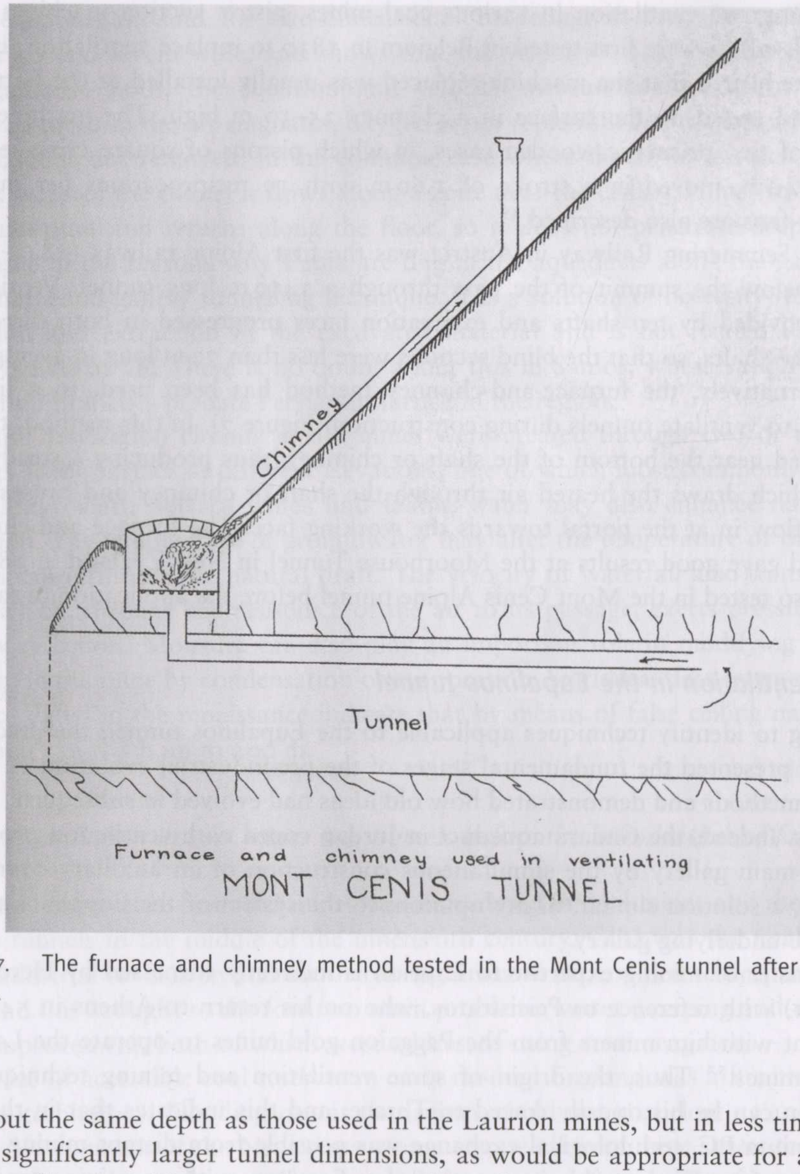

FIGURE 7. The furnace and chimney method tested in the Mont Cenis tunnel after Robert (1909).

of about the same depth as those used in the Laurion mines, but in less time and using significantly larger tunnel dimensions, as would be appropriate for a huge project of its time. However, the number of lives lost was also unprecedented.

Typical section of the Eupalinos' tunnel is shown in Figure 8. On the eastern wall the top of a shaft is shown in the foreground connecting the tunnel floor with the underlying gallery. The gallery runs a few metres below the tunnel floor inclined southwards all along the tunnel; it is connected to the supply sector in the north and the distribution sector in the south and contains the water pipeline. The interconnecting shafts are vertical about 10 to 15 m apart covered today with a metallic grid for the protection of the visitors. It is noted that the tunnel roof is inclined along the bedding plane of the host rocks, marls or limestones.

In the case of the Eupalinian tunnel, Burns suggested that 'the second (lower) tunnel was dug to provide the slope and that 'ventilation may have been a

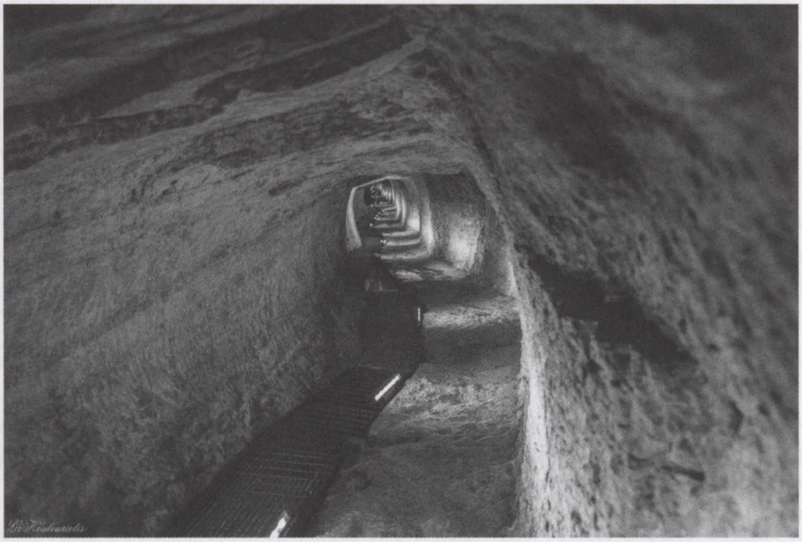

FIGURE 8. Typical view of the Eupalinos' tunnel looking northwards, in photograph by G. Koulouriotis.

factor'[53]. Kienast did not examine the ventilation scheme, whereas Zambas proposed that a trench was excavated to one side of the tunnel, separated with a wooden floor sealed with clay.[54] However, partitioning the heading with a wooden brattice is inefficient and reported to operate 'only to a relatively feeble extent, since the masses of air reside in the same plane'.[55]

The only certainty is that the long blind segments of the Eupalinos' tunnel could not be excavated, safely, without a system of adequate ventilation; this would require two mouths for each tunnel segment. We propose as a possible solution that a temporary horizontal or slightly inclined gallery below the tunnel provided the second opening for ventilation and was also used for the drainage of the ground water which abounds in the tunnel through a lateral inclined canal (Figure 9a,b). Thus, the tunnel sectors and the auxiliary gallery below would be necessarily dug simultaneously and after the crossing the sections of the auxiliary gallery would be modified with sloping floor for the accommodation of the water pipeline. During tunnelling the tops of the shafts would be closed apart from the shaft the nearest to the excavation face, as marked in Figure 9.

Even so, the Eupalinos' tunnel segments are too long, and further ventilation enhancement would be perhaps needed. Groundwater in the tunnel presents a favourable factor in two respects: first, water disturbs the air-rock temperature equilibrium and the air stagnation; second, the waterflow transfers energy and moves the air in contact with it. Furthermore, the shaft near the south mouth connecting the tunnel with the surface (Figure 3), supposed to be used for the transfer of alignment, is at the right position for air heating at a fireplace at the surface, like the chimney method described; however, a similar shaft in the north has not been found, but the nearest shaft of the supply branch could have been

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