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More light in the tunnel of Eupalinos

Costas Zambas

Mehr Licht im Tunnel des Eupalinos

ZUSAMMENFASSUNG Die am Tunnel des Eupalinos, einem singulären Monument und Teil der archaischen Wasserleitung von Samos, durchgeführten Restaurierungsmaßnahmen und aus diesen resultierende neue Erkenntnisse, insbesondere zur Auskleidung des Stollens, werden in kurzer Form vorgestellt. Zudem werden neue Hypothesen zum Entwurf der Anlage und dessen Umsetzung vorgestellt. Die Trassierung des Tunnels wurde zunächst mit Gerüsten auf dem Bergrücken markiert und anschließend zum Zweck des genauen Vortriebs mit zwei Lichtsignalen ins Berginnere übertragen, von denen eines sich nördlich auf der stadtfernen Bergflanke und das andere südlich auf einem hölzernen Turm in Meeresnähe befand. Im nördlichen Stollen führte steter Wasserfluss zu hoher Luftfeuchtigkeit und die resultierende dunstige Atmosphäre innerhalb der Anlage zum Verlust des Lichtsignals; dieses Problem löste Eupalinos, indem er die Trassierung von der Achslinie abweichend zu einer flachen V-Form modifizierte, durch die sich der Vortrieb korrekt dem Zielpunkt annäherte und ein exakter Durchbruch erreicht wurde. Das Bodenniveau des Tunnels wurde bereits im ursprünglichen Entwurf genau bestimmt. Der Graben an seiner Ostseite war ebenfalls bereits Teil dieses Entwurfs und wurde zeitgleich mit dem Tunnel angelegt; er ermöglichte die angemessene Bewetterung des Vortriebs. Die Bauzeit betrug maximal vier Jahre.

Schlagwörter Samos; Tunnel; Eupalinos; Trassierung; Bewetterung.

ABSTRACT The restoration works on the unique tunnel of Eupalinos, part of the Archaic aqueduct on Samos, and the information that the new evidence from them provides, especially on its linings, are presented in brief. New hypotheses for the design and the construction of the tunnel are also proposed. The center line of the tunnel was initially laid out over the hill surface with long scaffolding. Then, in order to ensure the accuracy of the excavation, the line was transposed inside with the help of two light signals, one on the opposite hillside to the north and one on a wooden tower near the seaside to the south. The problem of the loss of the northern signal on account of low visibility caused by the flow of water, which produced high humidity and consequently a misty atmosphere inside the tunnel, was solved by Eupalinos by the modification of driving a V-shaped deviation, by which he approached the target correctly and succeeded in making an exact breakthrough. The level of the tunnel was defined accurately in the initial design. The trench on the east side of the tunnel was also part of the initial design and was excavated simultaneously with the tunnel itself: it facilitated proper ventilation during the excavation. No more than four years were needed to finish construction.

Keywords Samos; tunnel; Eupalinos; alignment; ventilation.

Περισσότερο φως στο τούνελ του Ευπαλίνου

ΠΕΡΙΛΗΨΗ Παρουσιάζονται εν συντομία τα νέα στοιχεία που προέκυψαν από τις εργασίες αποκατάστασης της σήραγγας του Ευπαλίνου, ενός μοναδικού μνημείου, το οποίο είναι τμήμα του αρχαϊκού υδραγωγείου της Σάμου, καθώς και τα νέα στοιχεία που προέκυψαν από αυτές, ιδίως σχετικά με την επένδυση των τοιχωμάτων της στοάς. Προτείνονται επίσης νέες υποθέσεις για τον σχεδιασμό και την κατασκευή της σήραγγας. Η χάραξη έγινε αρχικά πάνω στις πλαγιές του λόφου με τη βοήθεια ενός επιμήκους ικριώματος και μεταφέρθηκε στη συνέχεια στο εσωτερικό του. Για να διασφαλιστεί η ακρίβεια της εκσκαφής, χρησιμοποιήθηκαν δύο φωτεινές πηγές: μία προς βορρά στην πλαγιά του απέναντι λόφου και μία προς νότο στην κορυφή ενός ξύλινου πύργου στην παραλία. Το πρόβλημα που προέκυψε από την απώλεια του βόρειου σήματος λόγω της υψηλής υγρασίας και της αποπνιχτικής ατμόσφαιρας, που δημιούργησε η συνεχής ροή νερού, επιλύθηκε από τον Ευπαλίνο με την τροποποίηση της χάραξης του βόρειου κλάδου με μια παράκαμψη σχήματος V. Έτσι προσέγγισε ακριβώς τον στόχο και πέτυχε την συνάντηση των δύο κλάδων. Η στάθμη της σήραγγας ορίστηκε με ακρίβεια κατά τον αρχικό σχεδιασμό. Η τάφρος στην ανατολική πλευρά της σήραγγας ήταν επίσης σχεδιασμένη εξ αρχής και διανοίχτηκε ταυτόχρονα με τη σήραγγα προκειμένου να εξασφαλιστεί ο αερισμός στο μέτωπο της εκσκαφής. Ο χρόνος κατασκευής της σήραγγας δεν ξεπέρασε τα τέσσερα χρόνια.

Λέξεις-κλειδιά Σάμος. Σήραγγα. Ευπαλίνος. Χάραξη. Αερισμός.

THE RESEARCH TO DATE

The admiration of Herodotus[1] for the tunnel of Eupalinos, which Herodotus considered as the foremost of the three largest technical works in ancient Greece, is echoed even today by scientists of various disciplines. The tunnel, which is the central part of the aqueduct of Samos, was excavated from two portals, set about 1 km apart: the two bores[2] met with high degree of accuracy at a depth of 175 m under the ancient fortification of the Kastro Hill *(fig. 1)*. The monument was cleaned in a systematic and archaeological way and was partially consolidated by the German Archaeological Institute (DAI) between 1972 and 1973[3]. The explanatory documentation was published in 1995 by Hermann Kienast and the archaeological findings were presented in 2004 by Ulf Jantzen[4]. The first publications by Kienast[5] attracted international scientific interest: even before his final publication, or a little after it, the first opinions in response to his conclusions appeared by scholars, who of course had made no original survey in situ[6]. (Study of the monument was limited before the campaigns of the DAI.)

The spring supplying the aqueduct near the small village of Ayiades, the Archaic underground collector cistern under the old church of Aghios Ioannis and a part of the trench near the spring, were all discovered by Victor Guérin in 1853[7]. The finding of the tunnel was made by the monks Kyrillos and Theofanis in 1882 under the guidance of the Hegemon of Samos Konstantinos Adosidis. The first reports were by Epameinondas Stamatiades[8] with a detailed description of the discovery, by Ernst Fabricius[9] with the first measurements and drawings of the cistern, the section of the tunnel, the meeting point of the two bores and of the Archaic lining and finally by Synesios[10] with the first direct measurement of the length of the tunnel. All are valuable pieces of research. Wolfgang Kastenbein, as a professional surveyor of mines (›Markscheider‹ in German), performed the first systematic survey and presented measured plans of the tunnel at the scales 1 : 5000 and 1 : 500[11]. After him, June Goodfield and Stephen Toulmin visited the site: they gave their opinion about the orientation of the tunnel, but they made no measurements and documentation[12].

Kienast's study is an original and painstaking piece of scientific work[13]. He described in detail the conditions of the discovery of the Archaic aqueduct[14] and presented plans of the systematic survey of the collector cistern at Ayiades. The first part from the spring to

As I consider this article supplementary to the documentation of the discussed monument by scholars of the DAI Athens, I am grateful to Katja Sporn and Reinhard Senff for including it in the Institute's journal. I thank the anonymous peer reviewers for their comments and I am indebted to Ulrich Thaler for the final editing and to Don Evely for his suggestions and corrections of the English text. I express my gratitude to all those with whom we worked together for the design and execution of the restoration project.

1 Hdt. 3, 60.
2 The term ›bore‹, common in modern tunneling, is taken to refer to each one of the two branches of the tunnel (cf. use in Zambas et al. 2016, 68–71).
3 Jantzen et al. 1973a; Jantzen et al. 1973b; Jantzen et al. 1975.
4 Kienast 1995; Jantzen 2004.
5 Kienast 1977; Kienast 1984; Kienast 1986/1987.
6 Before Kienast's final publication, a few articles were written about the meaning of Herodotus' description by Tempelis 1991a, about Eupalinos' solution of the two bores by Tempelis 1991b, about the alignment by Tempelis 1994, about an explanation of the two-storey tunnel by Tölle-Kastenbein 1991; Tölle-Kastenbein 1994, 29–38 and shortly after it by Grewe 1998, 18–28. 58–68, especially for Eupalinos' strategy for the alignment and the modification of the driving of excavation.
7 Guérin 1856, 305–319.
8 Stamatiades 1884.
9 Fabricius 1884, 165–192 pls. 7. 8.
10 Synesios measured the length of the tunnel with the use with long canes for the unpassable part of it and found it to be 1026 m long. Synesios 1899, 143.
11 Kastenbein 1960, plans 1. 2.
12 They examined also the possibility of the use of antique measuring instruments. See Goodfield – Toulmin 1965, 49 f.
13 At some points the work could only be done by hanging upside down. Kienast 2005, 16.
14 Kienast 1995, 1–10.

Fig. 1. General plan of the area (scale 1 : 20 000)

the tunnel is 890 m long: he found it to be constructed either as an open trench or as an underground excavation using the shafts-and-gallery (or qanat) method; the second part, the famous 1036 m-long tunnel, and the third part from the tunnel to the city, with a length of more than 1000 m were made by the shafts-and-gallery method.[15] For the tunnel, he surveyed in particular the Archaic linings, the trench and the galleries with the surviving ceramic water pipes; he noted that above them there are always shallow trenches, which were initially excavated during the construction of the tunnel and then were filled with the debris of the galleries. He characterized them as »bridges«. On taking into account observations in the area of the spring and in the galleries of the first part of the aqueduct, he concluded that the trench was deepened in a second phase of the work, after the completion of the tunnel, because of a subsiding of the spring[16]. He also described at length the sequence of the works for the construction, the function and the conservation of the aqueduct for the 1100 years of its life[17], until it was used as refuge in the 7th century AD[18]. Kienast's interpretation of the way the tunnel was designed is of major importance[19], both in his deployment of the documentation and in the decoding of the red marks with letters, inscriptions and lines on the sides of the tunnel[20]. The whole study is a unique scientific documentation of high quality as befits a unique monument.

15 Kienast 1995, 17–83. The drawings include two plans 3a and 3b, at the scale 1 : 500; these are a plan view and longitudinal section of the tunnel, with all the information, and also numerous figures giving typical sections of the aqueduct at various points.

16 Kienast 1995, 38. 51. 54 f. 102–104.

17 Kienast 1995, 85–127.

18 Kienast 1995, 183–186.

19 Kienast 1995, 129–174.

20 Kienast 1995, 148–163.

THE RESTORATION AND THE NEW OBSERVATIONS

The study for the restoration[21] and the supervision of the works[22] provided opportunities for additional surveys and observation of the tunnel for the first time since the campaigns of the DAI. The conclusions of the documentation are included in the sequence of isometric drawings of *figures 2–18*[23]. Isometric presentation was selected because it gives realistically and instructively all the features of the monument in a single drawing instead of requiring the combination of the plan view and the longitudinal section[24]. The drawings are given in this publication at the scale 1 : 200 for the isometrics and 1 : 100 for the sections that accompany them[25]. They present generally the geometry of the tunnel before the interventions, which are added with colored hatching. In addition, the state of preservation, the ancient red marks and inscriptions[26], the ancient cuttings, the later additions and all the data of the monument are recorded. Technical details with descriptions and specifications of the interventions are omitted, because of the small scale of illustration. The trench and the galleries below the bridges with the remains of the ceramic pipes were not accessible because they were closed with permanent steel meshes during the preparation of the study and covered with wood during the works. The visible open parts of the trench are indicated with dashed lines[27].

The interventions between 2013 and 2016 included restoration, conservation and enhancement of the monument[28]. The main restoration works were the consolidation of the vulnerable rock surfaces and the restoration of the linings, which are noted on the drawings of *figures 2–18*.

[21] The studies were undertaken by a multidisciplinary group consisting of Dr C. Zambas and his team, Civil Engineers and Architects specializing in ancient monuments acted as the team coordinator, Prof. K. Tokmakides, Aristotle University of Thessaloniki and P. Tokmakides as Surveyors, Prof. G. Tsokas, Geophysicist, Aristotle University of Thessaloniki, EDAFOS S.A. (Edafos S.A. 2009), Geotechnical and Geological Studies and V. Konstantinides & Associates, Electrical Engineers. G. Angistalis, O. Kouroumli and D. Kaltsas of Egnatia Odos S.A. were the supervisors of the studies. A study on the conservation and protection of the ancient marks and writings, the masonry linings, the rock surfaces etc. was also prepared by K. Papastamatiou from the Directorate of Conservation of Ancient and Modern Monuments of the Greek Ministry of Culture. Valuable assistance during the studies was provided by the Archaeological Ephorate section headed by Maria Viglaki.

[22] The construction was undertaken by EDRATEC S.A. (Director: A. Tampakopoulos, Foreman of the worksite X. Briolas and basic company executives V. Spiliadis, S. Tampakopoulou, Ch. Iliakopoulos). The restoration works lasted from 2013 till 2016 and were supervised by the Directorate for the Restoration of Ancient Monuments, headed by D. Svolopoulos via P. Hadjimitros, head of the constructions section, and A. Kalfas, V. Soulis, G. Soras and S. Spyropoulou supervisors. EDAFOS SA and Dr C. Zambas office in cooperation with Dr K. Papantonopoulos acted as Technical Consultants for the duration of the works. The Directorate for Conservation of Ancient and Modern Monuments was working in parallel, implementing their 2010 study. The local Ephorate headed by P. Hatzidakis assisted in the works, providing quick inspections, supervising the archaeological excavations and advising the Contractor. The necessary limited archaeological excavations were performed under the supervision of M. and P. Viglaki, Archaeologists. A first short description of the works is included in Zambas et al. 2016.

[23] The architectural and structural surveys were performed by C. Zambas, G. Thomas and E. Doudoumi based on the topographical survey by P. and K. Tokmakides. The drawings in ink were made by G. Thomas and on the computer by E. Doudoumi. The original scales were 1 : 50 for the isometrics and 1 : 25 for the sections (Zambas et al. 2010, pls. ΠΡ1–ΠΡ31). The drawings are modified by the author for this edition, including the final interventions, with further additions and English captions.

[24] The problem of describing and presenting this specific monument in drawings is analyzed by Kienast in the beginning of his account (Kienast 1995, 17).

[25] The drawings of the study were updated according to additional documentation prepared mainly by X. Briolas, foreman of the work site, who is the person who has spent the most time in the tunnel in modern times.

[26] The exact places of the marks and their sizes on the east wall are given. A new mark, which consists of two O's connected with a vertical line, was found on east side after the cleaning of the deposits in Ch. 422.5 (*fig. 9*). Some of the horizontal and vertical red lines are also presented. Some of the later inscriptions are noted with a gray color.

[27] The trench and the galleries are presented by Kienast 1995, plan 3 a. b.

[28] Zambas et al. 2016, 75–78.

Fig. 2. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 0–30

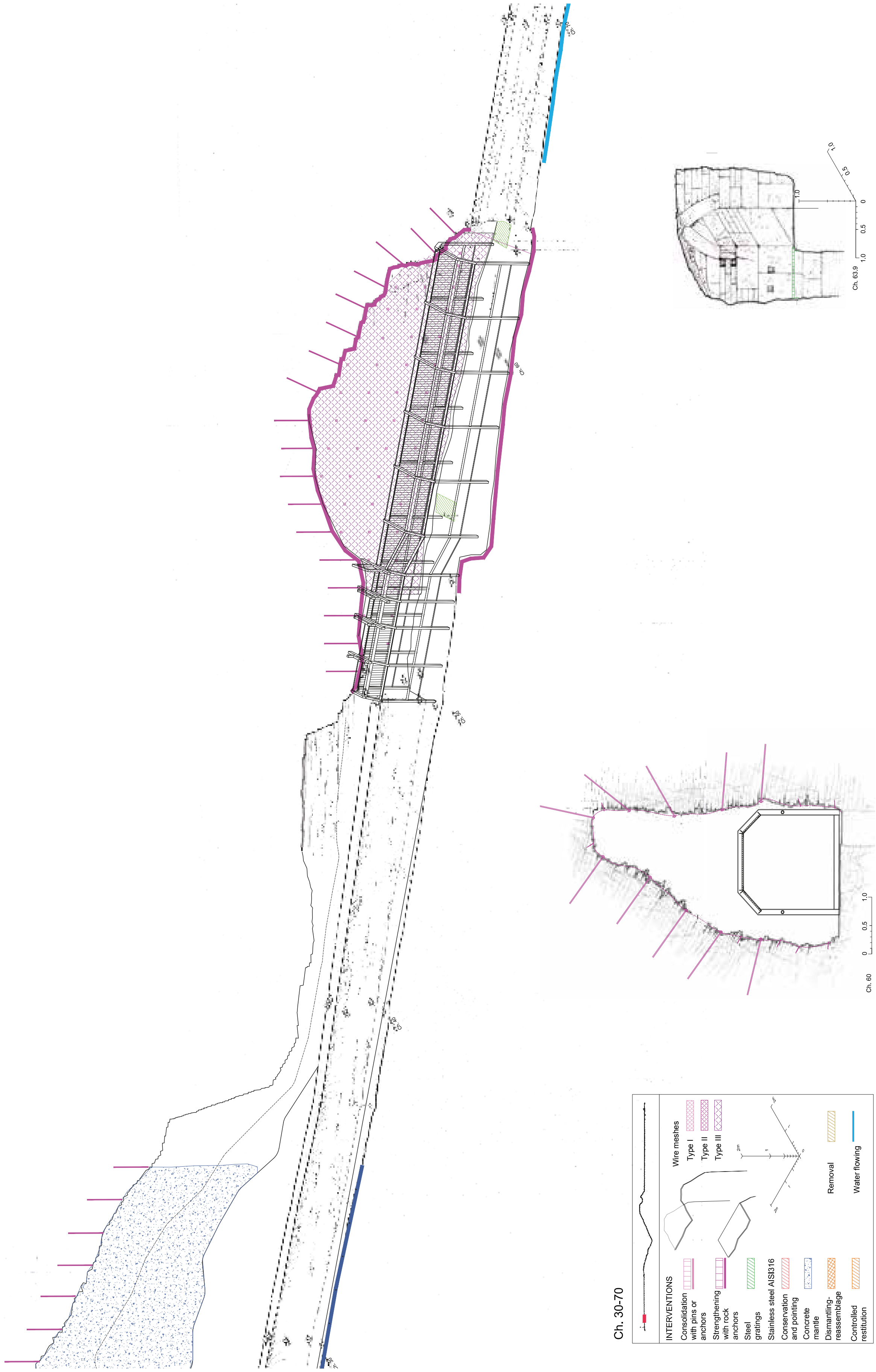


Fig. 3. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 30–70

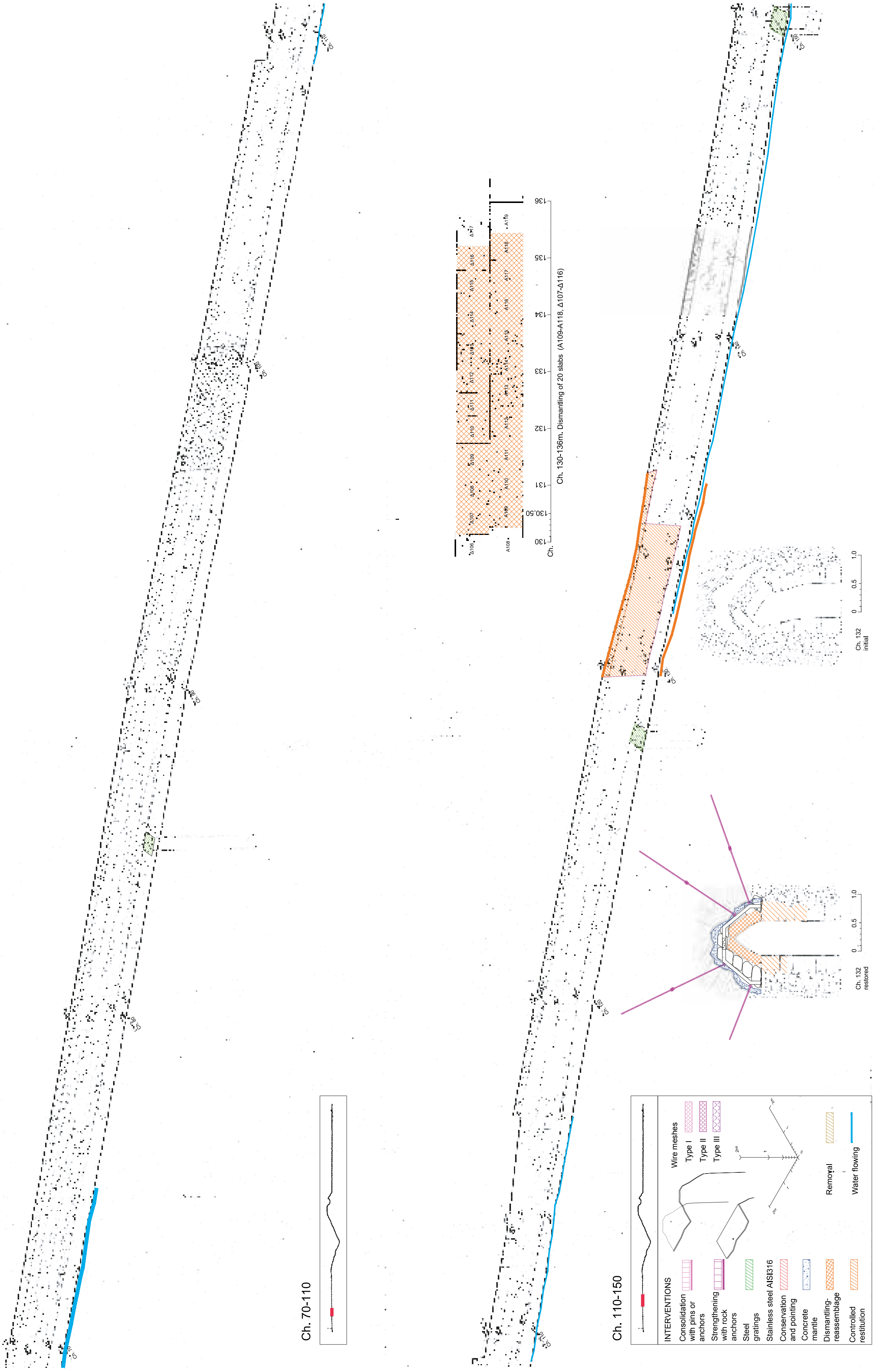


Fig. 4. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 70–150

Fig. 5. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 150–230

Fig. 6. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 230–315

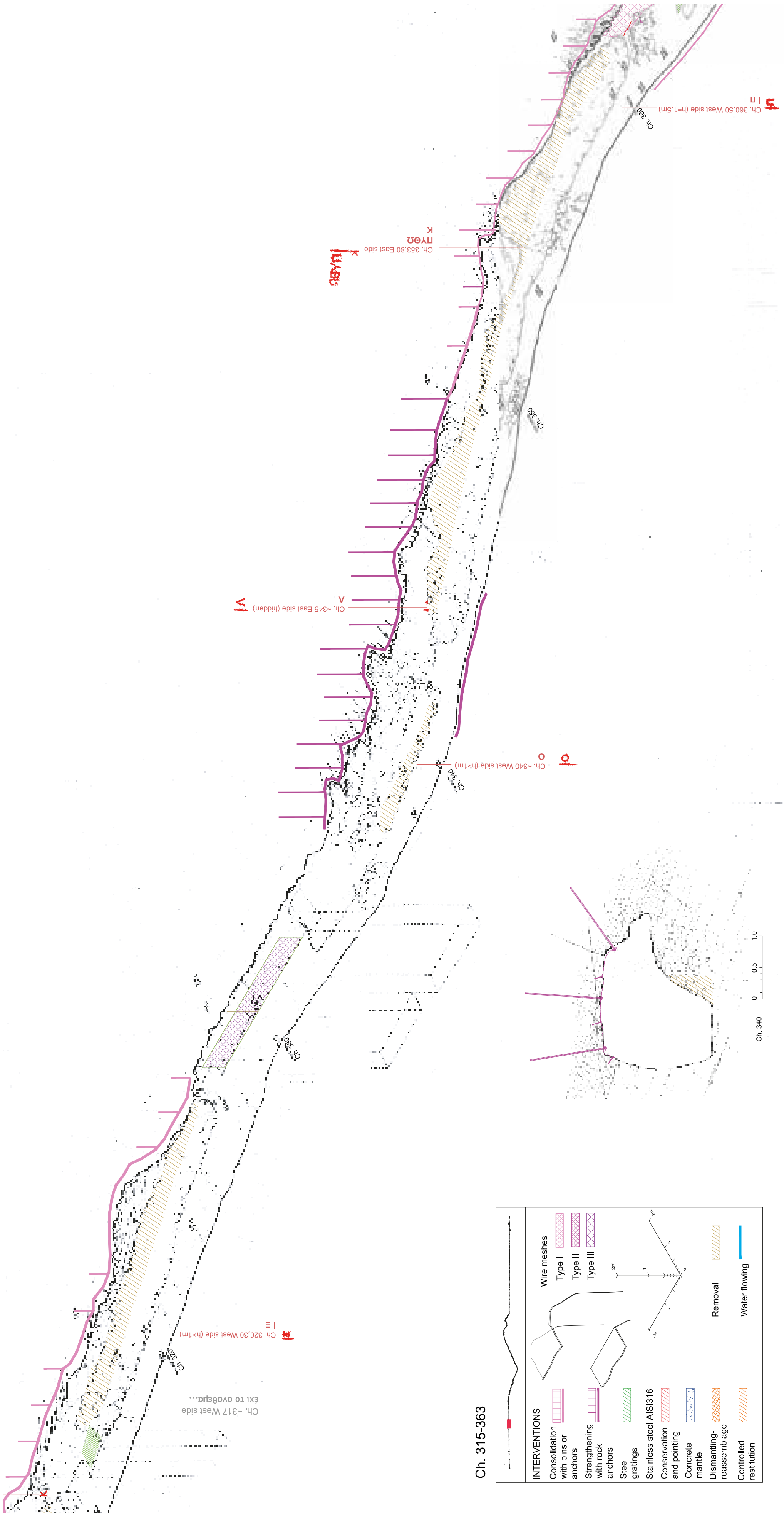


Fig. 7. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 315–363

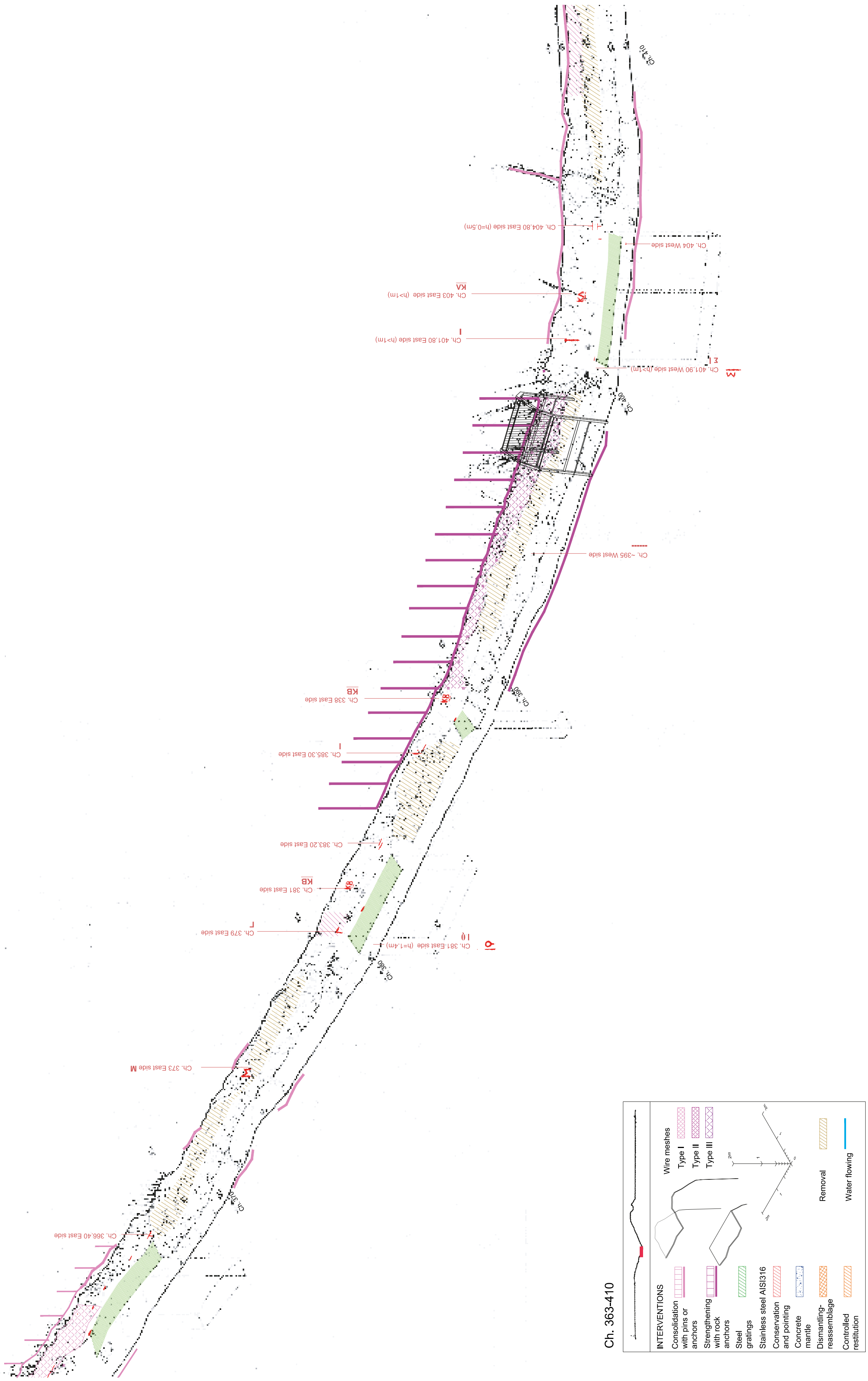


Fig. 8. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 363–410

Fig. 9. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 410–486

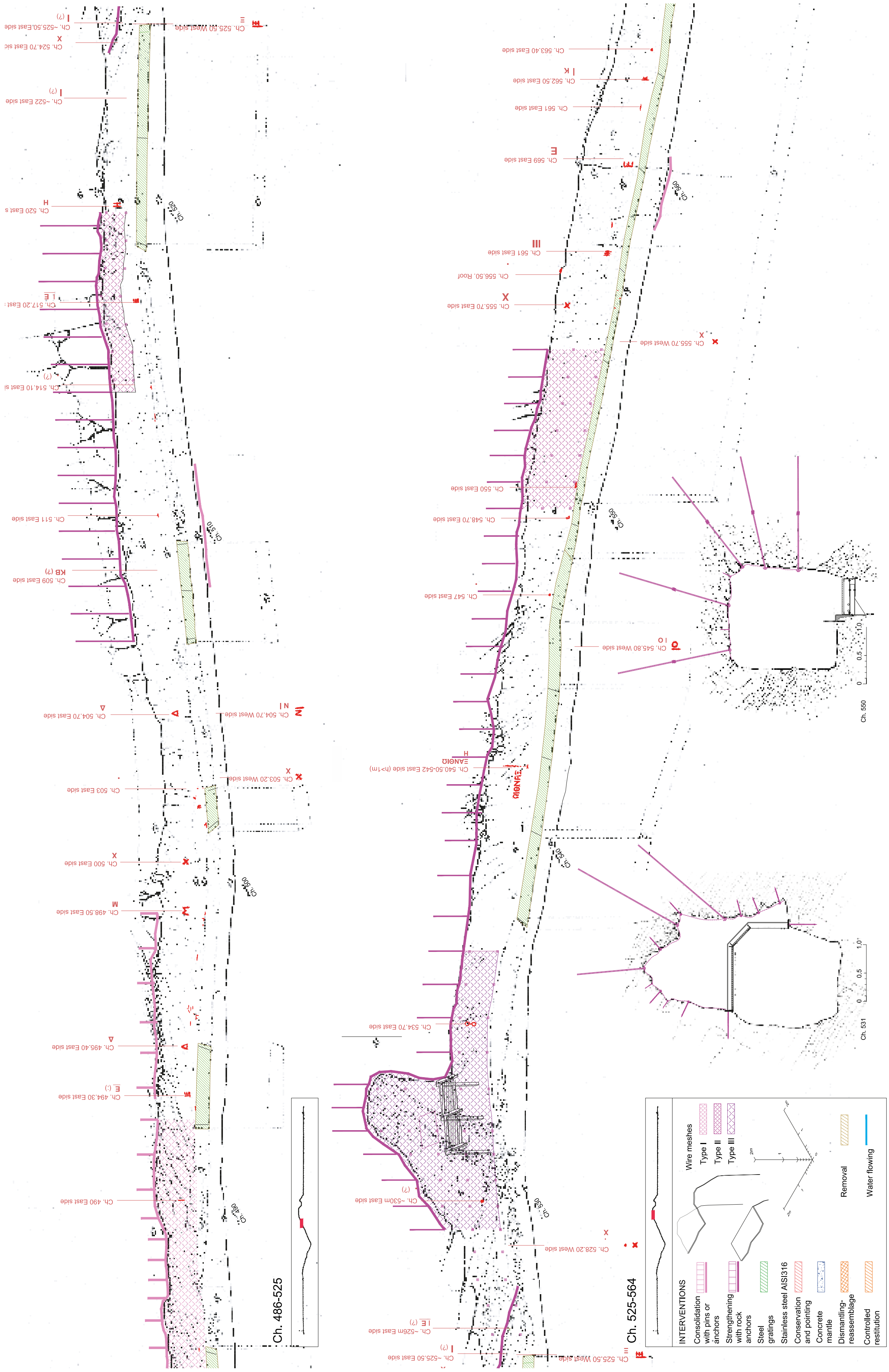


Fig. 10. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 486–564

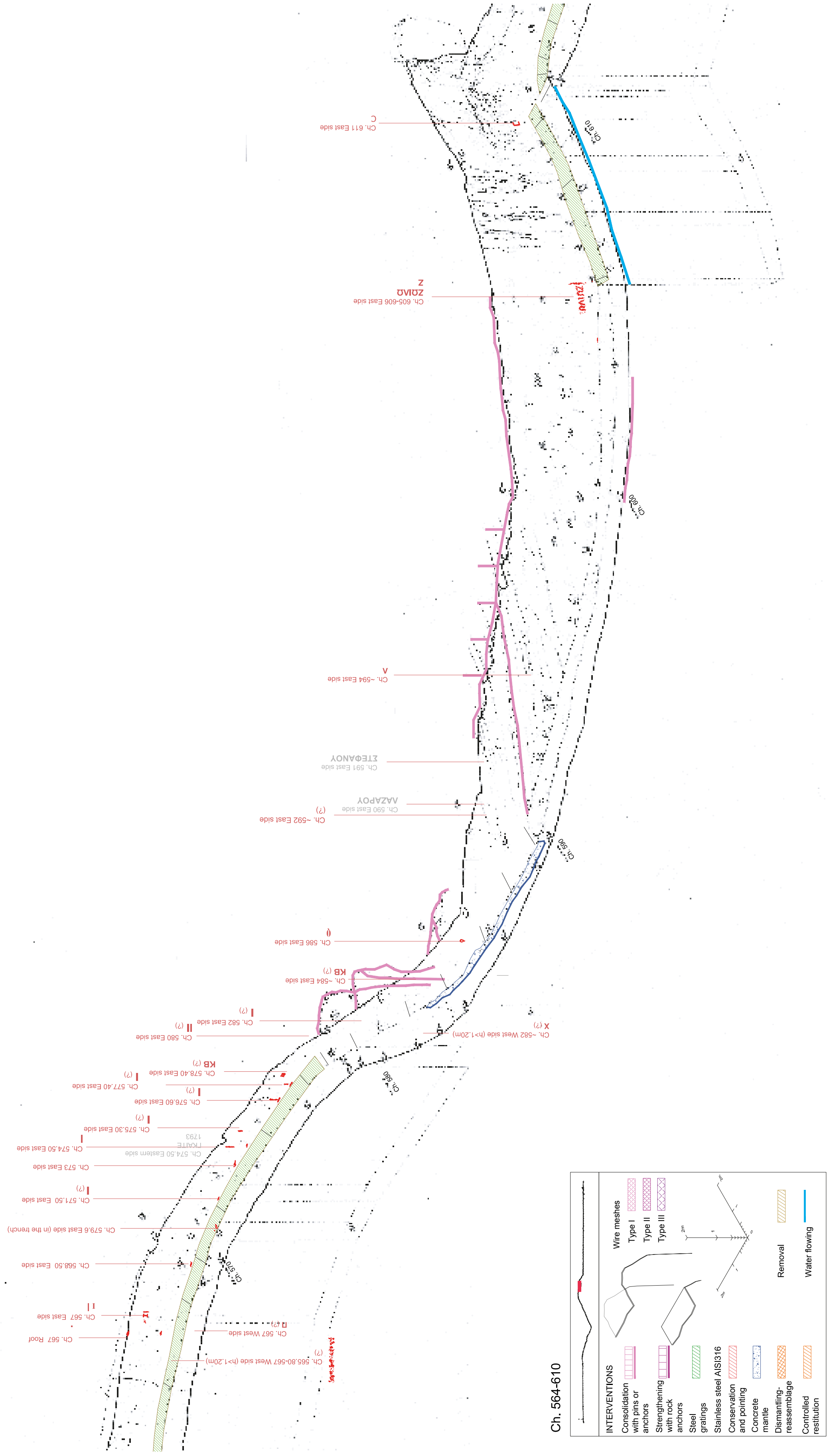


Fig. 11. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 564–610

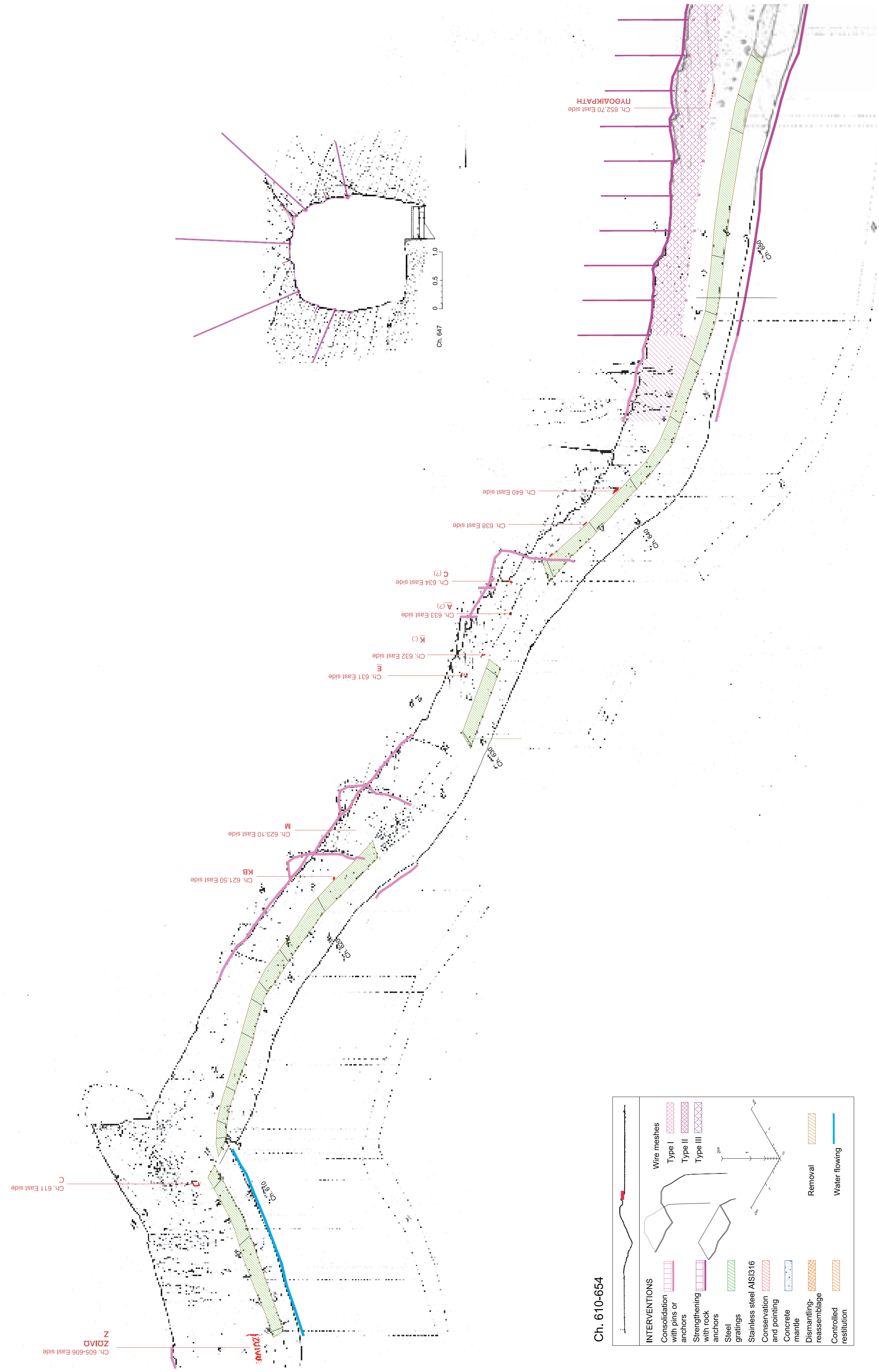


Fig. 12. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 610–654

Fig. 13. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 654–738

Fig. 14. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 738–820

Fig. 15. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 820–900

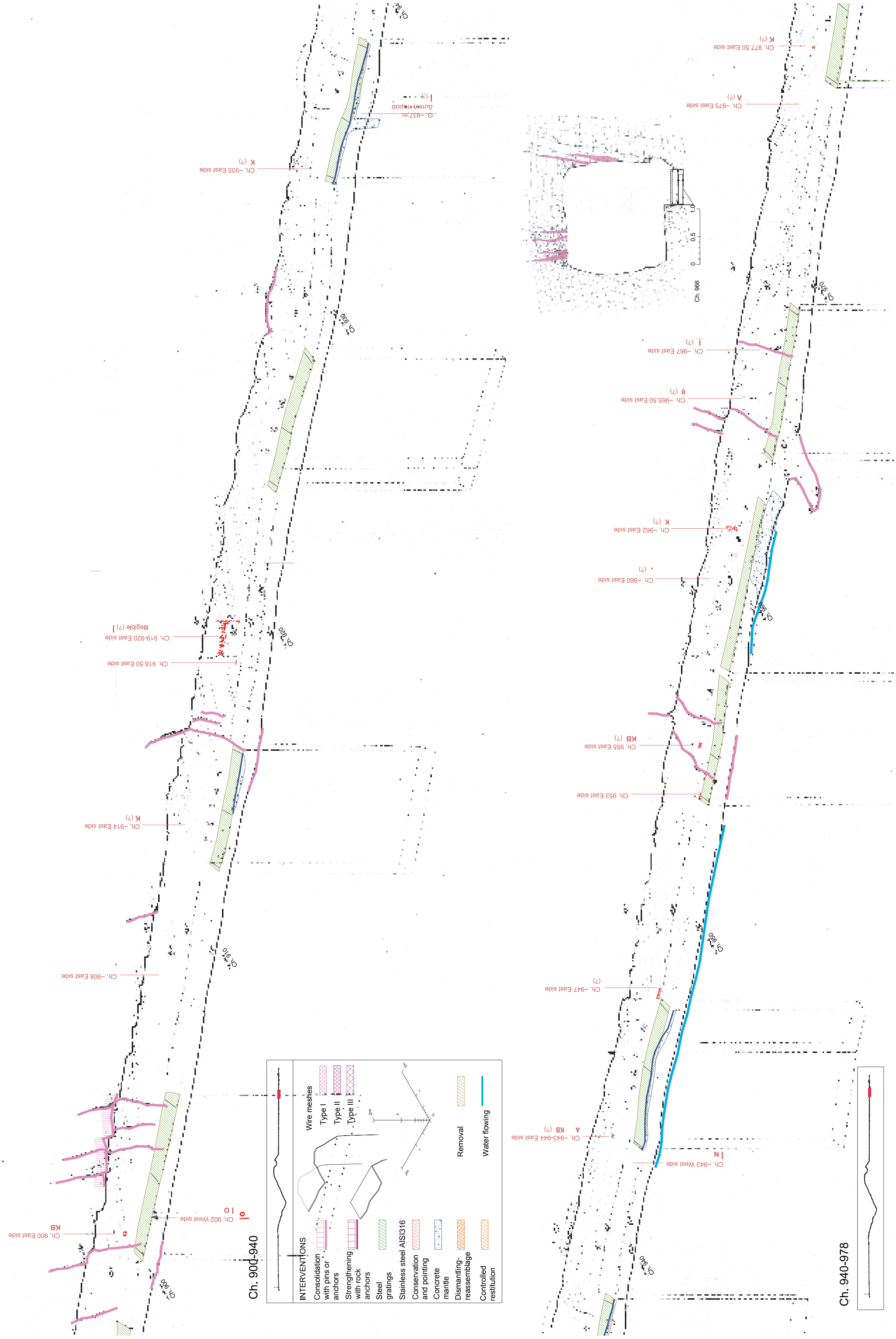


Fig. 16. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 900–978

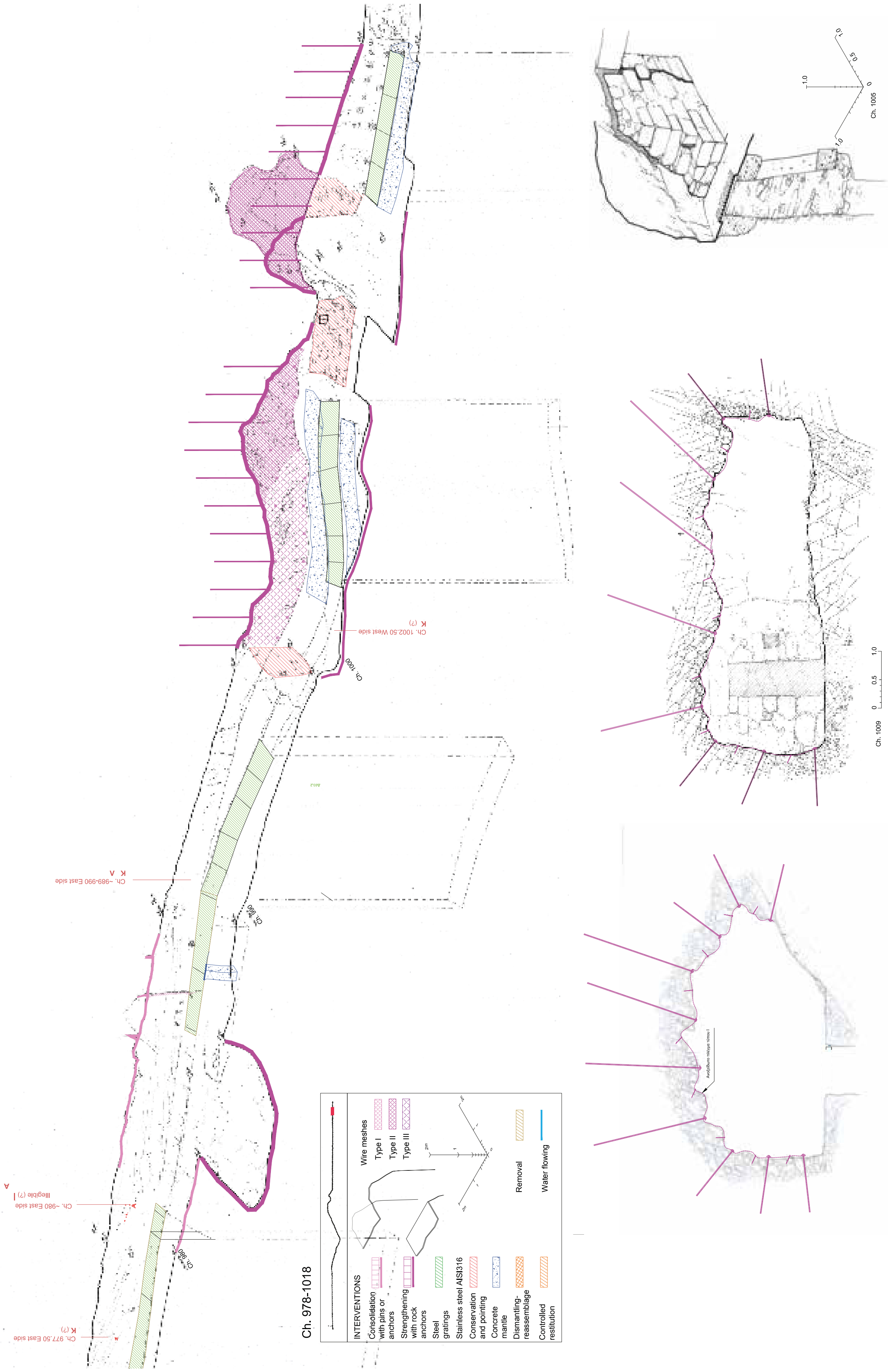


Fig. 17. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 978–1018

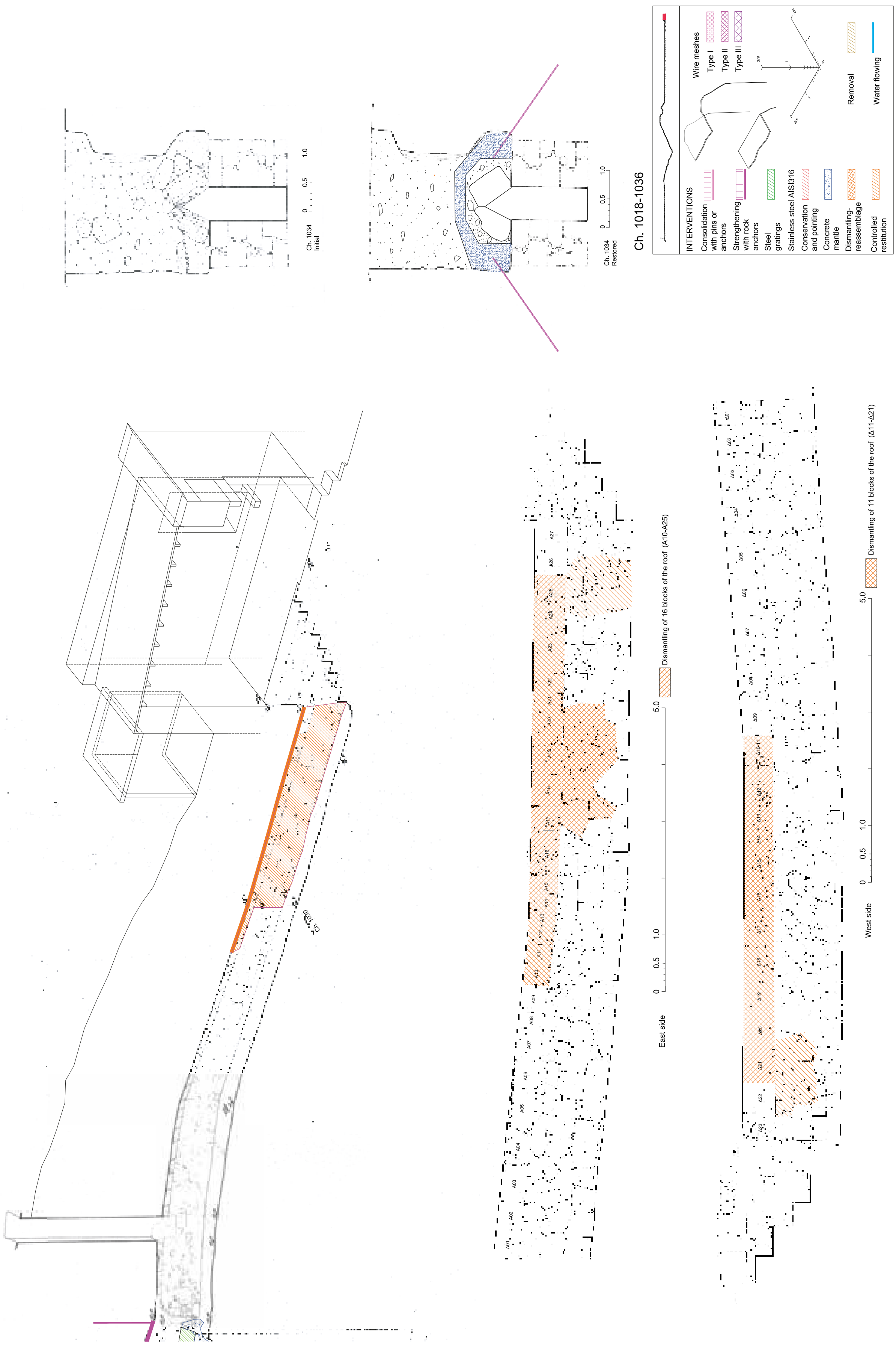


Fig. 18. Isometric plan of the tunnel of Eupalinos (scale 1 : 200) with sections (scale 1 : 100), Ch. 1018–1036

Fig. 19. The wire net with the anchors (Ch. 660)

Fig. 20. The protective canopy between the Archaic and the Roman lining, view from north (Ch. 49–63.9)

The consolidation and support of the vulnerable parts of the rock surfaces was made with grouting, rock anchors and a fine wire-rope mesh made of stainless steel AISI316. The great advantage in supporting the progressively collapsed areas with a combination of anchors and wire meshes is that all the surfaces remain visible, even ones of unworked rock exposed through damage, which are important only from the geological point of view. The visitor can safely pass along the tunnel and admire both the initial surfaces with the traces of the tools and at the same time the broken natural surfaces with their geological strata *(fig. 19)*. Thus he can understand the conditions faced by the ancient constructors: the variation in the rock's quality, the faults, the discontinuities, the synclines and the anticlines etc.

Fig. 21. The cave above the Roman lining protected by anchors and shotcrete

Fig. 22. The dismantling of the slabs of the archaic lining at Ch. 178.6, view from south

The tunnel is not only an archaeological monument, but a geological one as well. Three sizes of rock anchors were used, with diameters ø 12 or 16 mm respectively, with a length from 0.5 to 2.5 m and with especially designed spherical anchoring ends. Three types of flexible wire-rope mesh were also used according to the severity of the instabilities: (diameter of rope) X (mesh width in mm): Type I ø 1X30, type II ø 2X40 and type III ø 3X60. The wire-rope meshes are connected, with cables ø 3 to ø 5 mm, to the anchor plates with special end connectors and clamps.

For places of extreme vulnerability, an additional structure for the protection of the visitors was provided: the protective canopies. They are formed of steel beams and tubes and they are covered with steel gratings *(fig. 20)*. They fulfill the same purpose as the ancient linings, but they are light and ›transparent‹.

For the areas of less vulnerability, the thin and platy rock slabs of the roof were consolidated with pins, injections and the sealing over of open cracks.

The support of rock surfaces above or behind the linings, where not visible from the tunnel, was made with rock anchors, steel mesh and a shotcrete mantle applied with controlled low pressure. In *figure 21* is given a view of the supported areas above the Roman lining, which are not visible to the visitor.

Three parts of the Archaic lining of the tunnel – one near the inscription ΠΑΡΑΔΕΓΜΑ *(fig. 22)*, one more to the north and one immediately after the south portal *(fig. 23)*, which were seriously damaged and distorted – were dismantled, repaired and reassembled. For the southern one, a new protective slab made of reinforced concrete was constructed above the stone blocks of the roof and for the other two the rock was strengthened with rock anchors and covered with reinforced shotcrete mantle.

The Roman and Byzantine masonry linings were conserved with cleaning, pointing and filling open joints with mortar; any damaged masonry blocks were restored. A part of the Byzantine masonry which was seriously deformed was removed. The heavy trapezoidal covers of the trench remain visible, because they are an important part of the evidence of the monument[29]. The floor of the tunnel was covered with sand in the areas where water flows.

For the enhancement of the monument the trench was covered with heavy duty removable gratings made of stainless steel *(fig. 24)*. The gratings enlarge the floor space available for the movement of the visitors. Their level is the same as the ground level of the bridges above the galleries, so the free height for the visitor is more than that above the rock floor. The bearing structure for the gratings consists of transverse beams securely fixed into the east and west sides of the trench and of pairs of longitudinal beams resting on them. The west edge of the trench, which was broken and had been temporarily restored with concrete, was cleaned and carefully reconstituted with fresh hydraulic lime mortar, thus preserving and improving the ancient cuttings. The whole appearance of the tunnel has drastically changed: now one can have an unimpeded view of it, after the replacement of the old projecting and rusted steel bars by the new inox gratings.

The tunnel is now illuminated with linear and spot LED lights as a whole, and more locally at the places where the Archaic red marks are *(fig. 25)*. The trench is also illuminated with LED spots. As a result the visitor can see and understand the main point of the construction of the tunnel, which is the installation of the ceramic water pipes at the bottom of the trench and of the galleries. After the restoration works, the tunnel is protected and safe for visitors, with more light throughout its length.

The new observations on features of the tunnel, which follow, were made mainly at the areas were Kienast had no access: they were either above the Roman lining after the north portal or behind the dismantled Archaic linings. The zero point of the chainages (Ch.)[30] is on the lowest step of the modern stair of the north portal, where it was also defined by Kienast *(fig. 2)*[31]. At Ch. 10, we meet the intersection of the tunnel with the very high gallery of the aqueduct coming from the spring. At the bottom of the meeting point survives the rectangu-

29 For these slabs see Kienast 1995, 120.

30 The term chainage (Ch.) is used for the length measurements for linear structures as roads and tunnels. It is derived from the surveyor's chain (›Lachterkette‹ in German) one of the oldest measuring instruments (halysis) that is mentioned twice by Hero (Lewis 2001, 20 f.). It was extensively used in tunnel surveying of 19th century and was known as the Gunter Chain after clergyman E. Gunter, Professor of Astronomy in England, who invented it in 1620.

31 Kienast 1995, 42 fig. 10. The chainages were marked by Tokmakides' group on inox plates screwed on the rock surfaces of the west side of the tunnel every 10 m and their coordinates were defined. There are slight differences in some places with Kienast's older tablets, but these are not important.

Fig. 23. The excavation near the south portal and the dismantling of the blocks of the roof of the Archaic lining, north on the left

Fig. 24. The tunnel with the steel gratings and the new illumination with LED lights, view from the north (from Ch. 855, before the inscription ΑΡΙΣΤΕΙΔΩ)

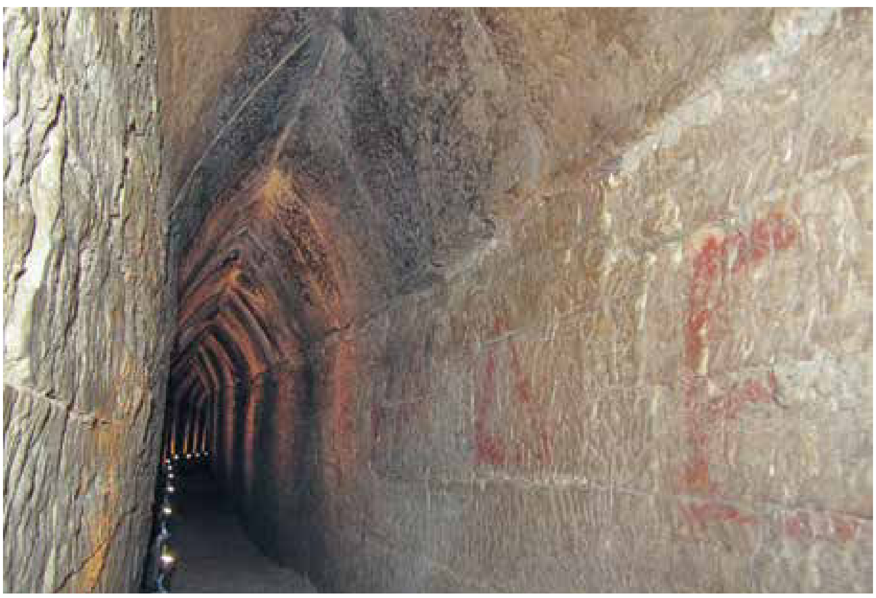


Fig. 25. The Archaic lining with the new illumination with LED spotlights, view from the north (from Ch. 174)

lar stone structure for the connection of the ceramic pipes[32]. The stair and the wall at the east side before the junction are constructions of the 19th century after the discovery of the tunnel *(fig. 2)* [33]. Immediately after the junction there are two walls facing both sides of the tunnel, which after 4 m is covered with a cylindrical vault and a lining: this continues for 35 m until Ch. 49. This lining is considered by Kienast as a structure of Roman times, taking into account its structural characteristics[34]: plate-like stones built with wide joints, filled with mortar. The next part with a length of 14.5 m is a very unstable part of the tunnel, which after successive collapses now has a height more than 6.5 m and was protected by DAI with steel frames and metal sheets[35]. The whole area was strengthened with rock anchors and heavy wire-rope mesh; additionally a new protecting canopy made of stainless steel beams and gratings was constructed up to the beginning of the Archaic lining at Ch. 63.9 *(figs. 2. 20)*.

Access above the Roman vault was impossible during the preparation of the restoration study. The space was cleared in the course of the interventions and it was found that the height of the rock roof was much more than had been estimated. A large cave and a rock chimney above it had formed because of the collapse, reaching a maximum height of about 8 m above the vault. The thickness of the layers of the fallen materials was up to 6 m *(fig. 2)*. The remaining thickness of the rock mass up to the surface level of the hill had decreased to 8 m. This type of progressive collapse with the formation of a chimney is typical for this type of rock mass[36]. A large part of this material was removed in a systematic and archaeological way: it was found that the lower layer included finds of the Byzantine period and even a construction with stone steps[37]. The rock was then supported with shotcrete mantle and rock anchors *(fig. 21)*.

The unit of rock mass between Ch. 20 and Ch. 63.9 is characterized as »shaly-thinly bedded alternations«, comprising a weak and heterogeneous unit consisting of alternating platy limestones, marls and clay shales[38]. The condition of the rock mass is highly unstable, but it had remained free of any additional protective structure for many centuries from the beginning until the construction of the Roman lining. Since the Roman vaulted construction did not support the roof of the rock mass and there was always a gap of at least 0.5 m high between it and the extrados of the vault, this structure is not exactly a lining as in modern tunnels, i.e. a supporting structure, but a protective passage of remarkable strength, given that it supported a huge additional load from the masses that collapsed onto it. The protective steel structure that was constructed by DAI, extending for 14 m until the Archaic lining, had the same function as the new canopy of the recent restoration. With the new solution we have achieved both a protected passage with the canopy and a support of the rock mass with the anchors and the wire-rope mesh *(figs. 3. 20)*.

From Ch. 63.9 begins the lining. There are two parts: one with a length of 133.6 m up to Ch. 197.5; and after a further 46 m, another with a length of 20 m from Ch. 243.5 to Ch. 263.5 *(figs. 3–6)*. It is a structure of a great aesthetic value with an admirable durability and has survived in an excellent state of preservation. The lining consists of two vertical walls with a height from 1.3 to 1.4 m, at a distance from 0.60 to 0.68 m apart; a pointed barrel vault was set upon them, with its highest point at a distance between 1.8 and 1.9 m from the ground surface of the tunnel. The vault is formed by single slabs set opposite to each other, seated

[32] Kienast 1995, 43 fig. 11.

[33] Kienast 1995, 41.

[34] Kienast 1995, 39.

[35] Jantzen et al. 1973a, 84 fig. 13.

[36] Lyberis et al. 2014, fig. 12; Angistalis – Kouroumli-Arend 2014, fig. 10.

[37] The archaeological investigation was performed by the archaeologist P. Viglaki, with the supervision of the archaeologist M. Viglaki. The future publication of their conclusions will be of great interest for the use of the tunnel as a refuge in the 7th century A.D. For this use, see Jantzen et al. 1973b, 410–414; Kienast 1995, 183; Jantzen 2004, 347.

[38] Lyberis et al. 2014, 7.

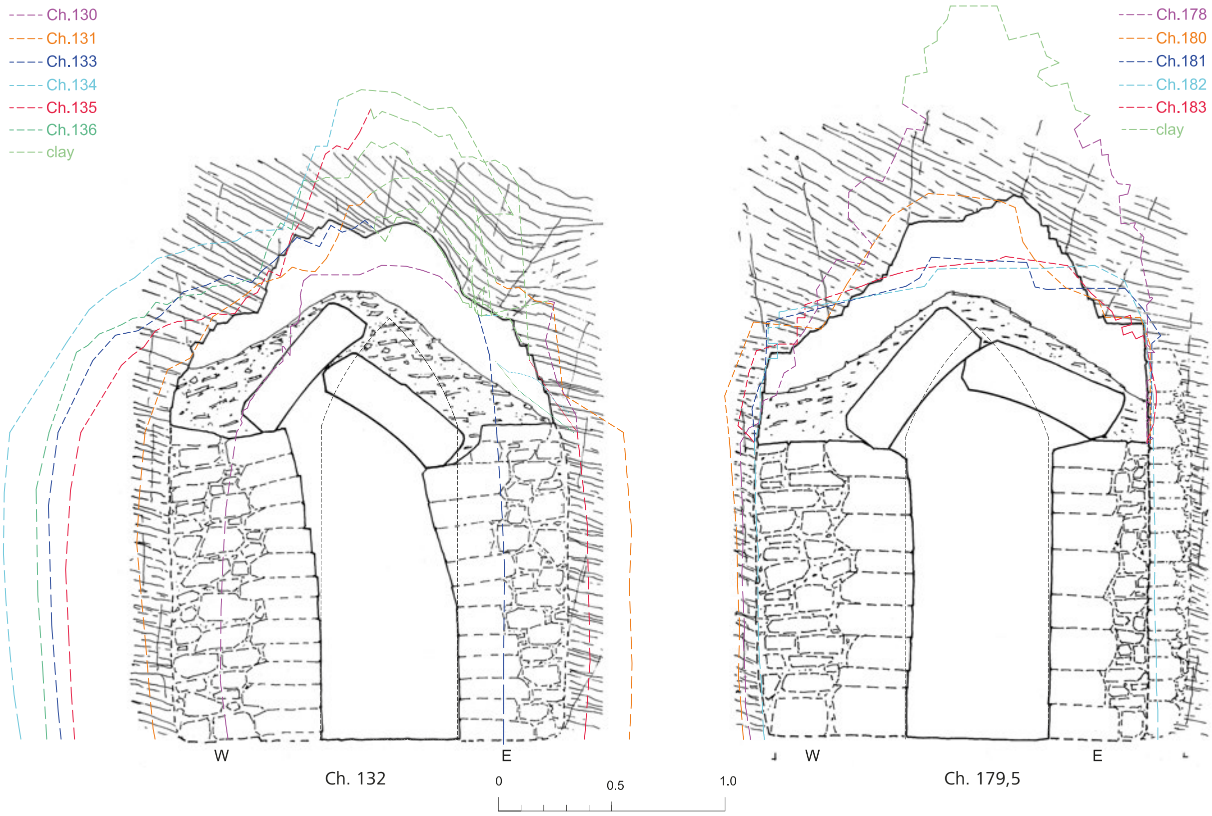


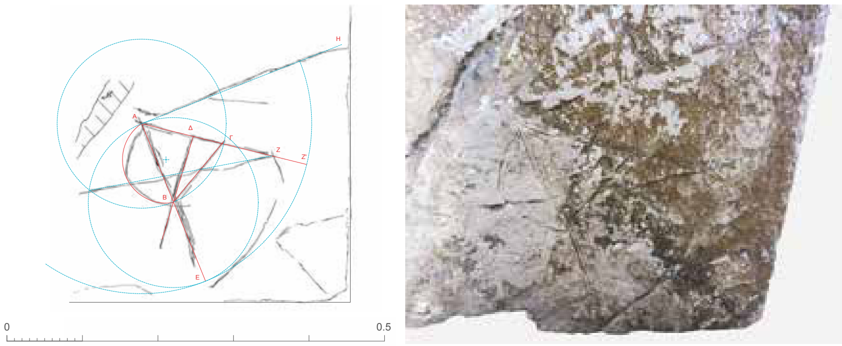
Fig. 26. Sections of the Archaic lining (scale 1 : 33⅓)

on the walls. Their visible surfaces have a curvilinear section with a chord between 56 and 59 cm and a sagitta about 3.5 cm[39]; in some cases they have a rectangular molding above their juncture with the wall. From the structural point of view, the linear equivalent of this type of roof is the three-hinged arch. In *figures 3–6* and *18* we give for the first time the measured sequence of the slabs of the roof of the east side and with dashed lines the joints of the opposite slabs of the west side, which are not visible in the isometric presentation.

Only four parts of the lining suffered serious deformations: between Ch. 96 and Ch. 100, where a partial reconstruction of the east wall with bricks took place during the interventions by the DAI[40], between Ch. 109 to Ch. 117 (*fig. 4* above), where the two walls have become deformed inwards and the minimum width of the tunnel, reduced to about 43 cm, is observed and two parts from Ch. 130 to Ch. 136 (*fig. 4* below, upwards view Ch. 130–136, section Ch. 132, *fig. 26* left) and from Ch. 178.6 to Ch. 183 (*fig. 5* above upwards view 178.6–183, section Ch. 179.5, *fig. 26* right), where the roof was dismantled and reassembled during the restoration works. From the first part, 20 slabs of the roof were dismantled, 10 from each side, and from the other 15 slabs, 7 from the east side and 8 from the west. The serious deformations of the walls were corrected with partial dismantling, but mainly with controlled forced restitution: the deformations were continuously monitored for each step of the mechanical application of lateral forces. For the first time we had the opportunity to examine the inner sides of the lining in quite extended parts.

39 The sections of the visible parts of the slabs are drawn as circular arches in *figs. 3–6*. In some cases this is true, but in others their curvature decreases at both ends and their shapes are closer to an elliptical arch. It is clear that there was no need for a strict execution in the design of the roof, thus leaving a freedom for the masons both for their dimension and the form. For such a project the overall aesthetic result is admirable.

40 Jantzen et al. 1973a, 81 fig. 10.



a b

Fig. 27. Slab Δ110 with the incised geometric design: a. Drawing (scale 1 : 10). – b. Photograph.

The quality of the rock mass is poor, similar to that above the Roman lining: platy limestones, marls and clay shales. In *figure 26* the successive profiles of the rock every 1 m, like in a tomography, for both parts are given[41]. We note a similar failure mode as above the Roman lining: collapse with formation of chimneys, where there is wet green clay. Especially in the part between Ch. 130 and 136 the width of the tunnel varies significantly with remarkable curvature on the west side and the thickness of the wall varies respectively[42]. It is obvious that the quality of the rock did not permit a linear excavation. The broken plates of the rock fell on the slabs of the roof and produced the deformations of the lining.

The walls are built of stone blocks with all their sides carefully dressed, except the back one, which was left as it was formed in the quarry. The dressing is of high quality, especially on their front surface, where the variety of the traces of the tools produces an impressive aesthetic effect[43]. The thickness of the walls varies from 0.5 to 1.1 m and that of the slabs from 10 to 50 cm. The space between the stone blocks facing the walls and the surface of the rock behind is filled with platy stones of varying thickness; these are placed in a systematic manner and the irregular joints between them are filled with soil. The wall was built by erecting the stone blocks in front and at the same time filling the gap between them and the rock with platy stones of the appropriate size. As a rule these stones are porous, and not of the same quality as the rock of the tunnel; among them there were found broken pieces with the characteristic curvature of the slabs of the roof. It is obvious that these last are fragments of the roofing slabs, which were never used[44]. The conclusion is that after the completion of the work of excavation and the removal of all the materials so created, another remarkable quantity of building material, stone blocks and platy stones for the wall and curved slabs for the roof were transported from a work site located outside the north portal into the tunnel for the construction of the lining. An interesting feature is observed in the east side between Ch. 178.6 to Ch. 183. Behind the wall there is another one, higher, built with treated platy stones, which supports a projecting part of the roof (*figs. 22. 26* to the right).

The lining was not designed as modern ones are, in which the blocks of the lining roof are in close contact with the surfaces of the excavated rock[45]. Looking at the four ends of

[41] Profiles surveyed by X. Briolas.

[42] The variation in the thickness of the wall was successfully estimated before the dismantling with the investigations by the ground penetrating radar (GPR) and electrical resistivity tomography (ERT) methods. See Angistalis et al., forthcoming; Tsokas et al. 2014, 282–290; Tsokas et al. 2015, 574–581.

[43] Jantzen et al. 1973a, 85 fig. 15; Kienast 1995, 45 f. fig. 12.

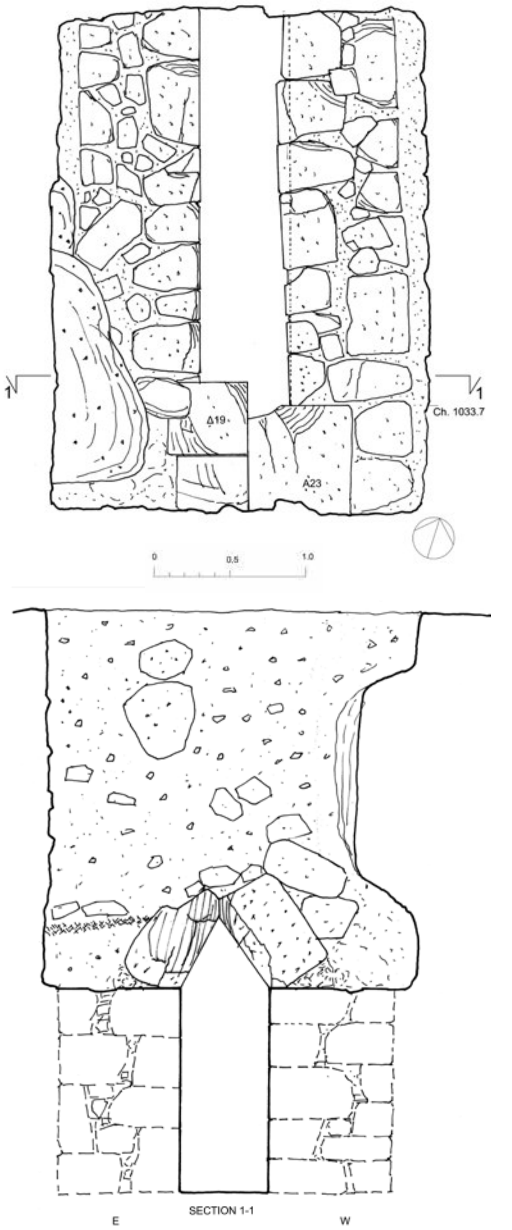
[44] The building material is possibly from the Archaic quarries on the opposite Katarouga Hill. For the quality of this stone, see Kienast 2012/2013, 144.

[45] The lining of the tunnels with bricks or concrete blocks is in contact with the surfaces of the rock. See Lauchli 1915, 108–115. The tunnels of today usually have a lining made of shotcrete covering the surface of the rock.

the two dismantled parts, we found that there were gaps behind and above the undisturbed roofing slabs. Where we found materials behind them, they had fallen from the roof *(fig. 22)*. Such falls were able to slide sideways, leaving space for further falls – and that is how the chimneys were formed.

On the back side of the slab Δ110 (Ch. 132), an incised rough geometric drawing was observed, which is composed of straight lines and curves *(fig. 27)*. Some traces resulting from the natural layers of the stone or of corrosion make the overall picture complicated to read. Very clear are the incised lines AE, AZ, ΒΓ, ΒΔ and the curve AB drawn with a free hand, which are indicated with a red color in *figure 27 a*. The lines seem to be incised with a sharp tool, in a repeating action, one line close to another. The triangle ΑΒΓ is isosceles, very close to an equilateral one and the line ΒΔ marks the altitude of the triangle. The meaning of this geometric construction is not obvious. It seems like a mason's explanation of a geometric construction or possibly a comment on the V-shaped deviation of the north bore of the tunnel.

The lining of the south portal, which we meet immediately after the modern staircase of the south entrance, has a length of 13 m and runs from Ch. 1036 to Ch. 1023. It has remarkable morphological differences from the north lining. The walls are built with voluminous polygonal blocks, the roof is formed by slabs with level surfaces and its section is that of a triangular arch *(fig. 28 b)*. The walls had suffered serious deformations inwards and the slabs had severe structural damages. Many repairs have also been conducted since the time of the discovery of the tunnel and some of the slabs have been reconstructed. The first attempt to dismantle the slabs showed that the overlying material was very loose; we had collapses. We decided to proceed with a systematic archaeological excavation from above *(fig. 23)*. The soil material could be excavated by hand: it was again shown to contain Byzantine ceramic fragments, which means that it had already been moved once[46]. Near the bottom of the excavation at the east side, a linear stratum of burnt material was found, which is shown at the left side of the section in *figure 28 b*. Since the thickness of the ›slabs‹ of the roof is remarkably greater than that of the north lining and



a
b

Fig. 28. The Archaic lining (scale 1 : 50):
a. Plan Ch. 1031–1034. – b. Section Ch. 1033.5

[46] The archaeological report is to be published by P. Viglaki.

reaches 48 cm, it is better to use the term ›blocks‹ of the roof. The wall is built as a double-faced retaining wall with heavy blocks on both faces well bonded, and with infilling soil material between them *(fig. 28)*. The conclusion drawn is that the Archaic lining of the south portal is a heavy structure, capable of bearing the great loads from the pressure of the earth above, as the first 13 m of the tunnel was constructed with the ›cut-and-cover‹ method.

Taking into account the additional documentation acquired by the restoration study and after a reexamination of all the studies of the past and especially Kienast's one, we attempt in the next sections to contribute to the scientific discussion for the design and the construction of the tunnel.

DISCUSSION ON THE DESIGN AND THE CONSTRUCTION OF THE TUNNEL

As we noted above the most examined feature of the Tunnel of Eupalinos is what Herodotus emphasized: the »amphistomon« cutting. The first question is why Eupalinos decided to go through the hill, instead of around it either with a trench or with the qanat system. Opinions differ. Kienast recognizes that the way around the hill was an easy one, but he notes that the tunnel method was safer and shorter[47]. Tempelis wrote an article specifically arguing that the only reason for the construction of the tunnel was Eupalinos' ambitiousness[48]. Goodfield and Toulmin examined in detail the contour line which connects the two entrances, investigating the applicability of Hero's method for the leveling method: they noted its ravines and overhangs[49]. The southern part of this path was indeed used for the route of the Roman aqueduct: it follows a contour, however, about 15 m lower, where the slope is less *(fig. 1)*[50]. We have no data for the durability of the Roman aqueduct, while the evidence shows that the tunnel of Eupalinos was in use for more than a thousand years[51]. A possible construction at the edge of the hill where the slope was steep is not a durable solution. Loose rock brought down slope from above by rain would demand continuous maintenance. Further an aqueduct near ground level and running for a length of 3 km is obviously exposed to enemy attacks: just one breech is enough if someone wants to put it out of order. Having in mind these points, we must probably reject the accusation of Eupalinos' ambitiousness in favor of the hypothesis of the safety against enemy attacks[52].

There are four tasks to complete to ensure a good design of the tunnel:

- the selection of the proper orientation,
- the guarantee of the correct alignment,
- the exact performance of the leveling,
- the measurement of the whole length, as well as the lengths of the two bores with high accuracy.

[47] Kienast 1995, 15.

[48] Tempelis 1994. The same opinion was supported by Angelakis – Koutsoyiannis 2003, 1004, without a reference to Tempelis.

[49] Goodfield – Toulmin 1965, 52.

[50] Dimitriou 2003, 206. 210 f.

[51] Kienast 1995, 120.

[52] This was recognized very early by Stamatiades 1884, 13.

The orientation

For the orientation, Kienast examines two more alternatives besides that which exists: one to the west, giving a minimum length of tunnel and one to the east, eliminating the trench from the spring to the north portal, but he recognizes generally that the decision was based on surveying criteria[53]. Stiros added one more alternative to a more eastern solution that combined a shorter tunnel with a qanat part on the north end[54], but he recognizes what Apostol emphasized some years before, namely the need of a reference line to the north as long as possible in order to ensure the proper alignment of the tunnel[55]. Apostol notes also that there is enough free space southwards for a long reference line too.

As we note in *figure 29 b*, the contour lines at the level of the bottom of the tunnel (green isoline), approximately 55 m above sea level, both at the bottom of Kastro Hill and the opposite Kataruga Hill form a tripod shape with the edge of its north leg near the spring at Ayiades. The west leg is the Kataruga stream and 5 m above the east leg is an elevated plane with a small upwards slope. The longest linear segment produced by the intersection of this tripod with of all the possible lines, which begin from the walled west part of the ancient city, is the one towards the north leg. The length of the reference line of the selected direction is more than 310 m, while the other alternatives examined by Kienast and Stiros intersect the legs, leaving free segments of only between 30 and 40 m. It is also clear from *figure 29 b* that if they selected the northern point of the reference line B_o any rotation of the center line eastwards would produce a longer tunnel. Repeated inspections from the ridge of Kastro Hill and from the spring and a preliminary leveling of the area by Eupalinos' group could prove that this was the optimum direction of the tunnel. So we conclude that the selected orientation is the only solution ensuring the longest free reference line from the north portal to the opposite hillside and with the minimum length of the tunnel up to the walled ancient city.

The alignment

After the successful essential determination of the direction, the more complicated three tasks, listed above, follow[56]. We can find analogies for them in the tunneling practice of the 19th century AD, when there was an explosive progress of underground works and for a long time much of work was done by hand. So the study of the relevant bibliography is very useful. A serious advantage the 19th century engineers had was the employment of survey instruments able to solve the main design problem of the location of the center line of the long tunnels: in some cases they used astronomical instruments of large size[57]. This achievement was considered one of the most important discoveries of the 19th century[58]. The dioptra, which is the predecessor of the modern survey instrument, was invented by Hero six centuries after Eupalinos' achievement[59] and there is no indication for the use of a similar instrument then. Burns' hypothesis that Hero's geometrical method for the bypass

53 Kienast 1995, 93 f. fig. 27.

54 Stiros 2009, 219–221 fig. 3. See also Stiros – Kontogianni 2010, 869 fig. 3.

55 Apostol 2004, 37. The same is emphasized by Grewe 1998, 61 fig. 85.

56 Prelini summarizes them: »the first task of the engineer, after the ends of the tunnel have been definitely fixed, is to locate the center line exactly. This is done on the surface of the ground and its purpose is to find the exact length of the tunnel and to furnish a reference line by which the excavation is directed«. Prelini 1912, 9.

57 Prelini 1912, 11 f.

58 Routledge 1881, 247 f.

59 For an extensive analysis and presentation of dioptra, see Lewis 2001, 51–108.

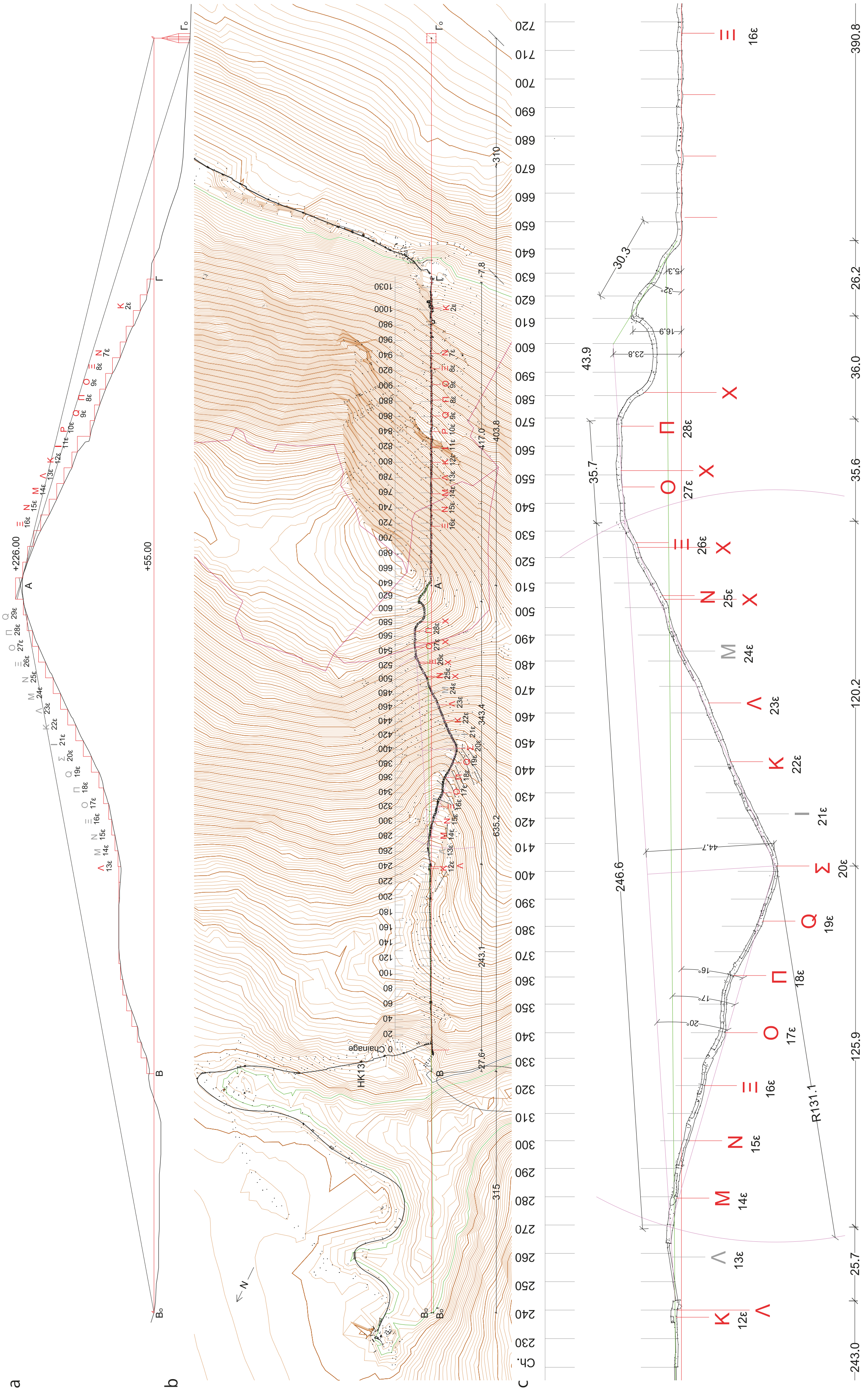


Fig. 29. Tunnel of Eupalinos: a. Section of the hill along the line connecting the two portals (scale 1 : 7500). – b. General plan of the tunnel (scale 1 : 7500). – c. Detail of the deviation and the meeting point (scale 1 : 2000)

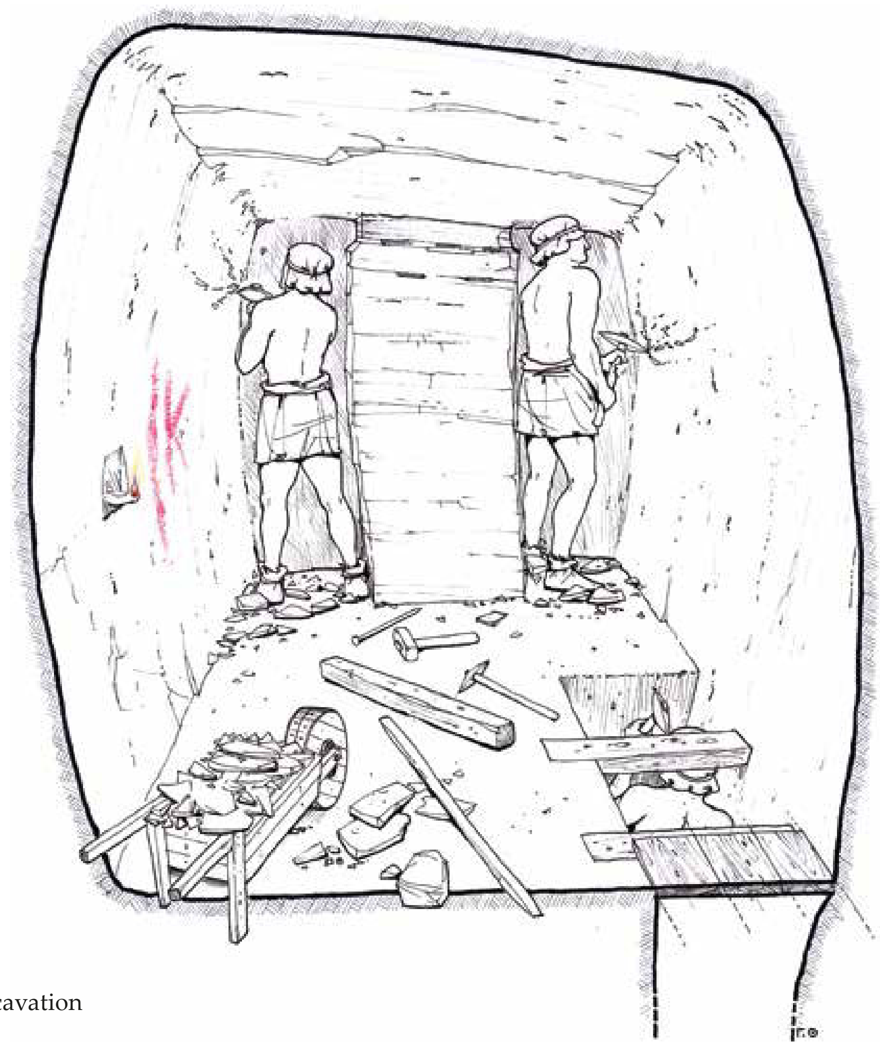


Fig. 30. Illustration of the excavation of the tunnel of Eupalinos

of the hill was used for the definition of the center line[60], the leveling and the measurement of the length of the tunnel has no justification: this method does not give the lengths of the two bores separately, but only their total length.

The center line of the tunnel has initially to be located on the ground surface and then to be transposed to the inside of the tunnel to drive on the excavation[61]. The best method that gives exact answers to all the questions is to map the location at surface level over the hill. The practical solution with poles for the alignment and with T-planks for the leveling, which was proposed by Grewe and was accepted by Kienast[62], are primitive practices, perfectly proper for preliminary estimations, but they do not give exact measurements for the alignment, the leveling and the determination of the length. The use of poles or small T-planks movable by hand means that for a sloping hillside we need countless measurements (about one every two meters) and the margin for error is considerable. A possible effective solu-

[60] Burns 1971, 176–183. This hypothesis was accepted by Apostol 2004, 34. 36, but it had been rejected many years before by Goodfield – Toulmin 1965, 53 f. For an overall examination of the old theories and other similar, see Kienast 1995, 8 – who voices the very justified opinion that they were developed theoretically, without taking consideration of the monument itself.

[61] This is a basic method for the tunneling of the 19th century A.D., as declared by Prelini 1912, 10 and other engineers.

[62] Grewe 1998, 27 fig. 29; Kienast 2005, 39 f. fig. 29; Kienast 1995, 131 f. fig. 33 n. 217, with thanks to Grewe for his proposal.

tion for the alignment, the leveling and the measurement of length would be the construction of scaffolding from one portal to the other. Similar scaffolding is proposed by Manolis Korres for Hadrian's Aqueduct in Athens, which was constructed by the qanat method[63]; it was usual in the tunneling practice of the 19th century[64]. The ancient Greek architects and technicians were very efficient in the attainment of high accuracy in the construction of large scale buildings, such as the Temple of Hera on Samos and about one century later the Parthenon in Athens. It was perfectly reasonable for them to apply the methods of building technology to the needs of land survey and for a much longer structure, such as the tunnel of Samos. With extended modular scaffolding in long steps they could achieve an accuracy of 1 mm for each step: they might be only few centimeters out over the whole length in aligning, leveling and length definition. The modulus for the steps could be equal to the modulus for the ancient chainages: something which was recognized by Kienast as being marked with the letters I to T. It here is estimated to be: ε= 20.56 m[65]. In *figure 29 a* an outline of such scaffolding is given with 29 steps on the north side of the hill and 18 on the south. The letters of the chainage from both ends are transformed to the steps on the section of the hill[66]. The terminal points at each end, B for the north and Γ for the south, were defined by Kienast, extrapolating from the last surviving letters near the portals of the tunnel[67]. The general elementary method of geodesy for the alignment of the connecting line with successive approaches or trial and error is well described by Grewe[68]. Sighting from the points $B_{o,}$ where the center line meets the isoline +55, and Γ_o at the extension to the south, we can define on a tall wooden tower on the top of the hill, where the ground is level for a length of 30 m, the point A belonging to the line BΓ with high accuracy, because of the very long distances open to the viewer. On wooden frames constructed at distances approximately equal to the modulus, longitudinal wooden beams are placed with additional intermediate struts. The maximum height of these frames is 10 m with one exception at 10*ε from south. Each frame is placed in a vertical position and each horizontal beam is leveled by the usual methods available in building technology. Sighting from B_o and Γ_o, every point of the chainage lying in the same vertical plane on both hillsides can be determined with high accuracy *(fig. 29 a. b)*.

Such scaffolding is useful only for obtaining the exact measurements, the definition of the central line on the surface of the ground and the accurate location of the terminal points B and Γ. It could be afterwards dismantled and used for other great projects. It is astonishing to note that the scaffolding necessary for the construction of Rhoikos temple needed approximately the same quantity of wooden elements as did the tunnel[69]. With the help of this structure the center line on the hill surface and the terminal points for the two portals would be defined exactly on the ground. The measurement of the lengths of the two bores to be made could also be made with high accuracy.

63 Korres 2002, fig. 1.

64 See the drawing of the large wooden ranging frame, after the cover page of Simms 1860.

65 The modulus has the value ε = 20.59 m according to Kienast 1995, 150 f. We propose here a new estimation a little less in value, taking into account his and our measurements. The accounting is omitted because of its technicalities. We note in *fig. 29* that the minimum distance between the letters of the ancient chainages is 19.7 m (Ξ–O of the north bore 17*ε from the point zero) and the maximum 21.9 m (K–Λ of the north bore 23*ε from the point zero).

66 The section is with a vertical plane passing from the line connecting the two ends.

67 Kienast 1995, 152 f. fig. 40.

68 Grewe 1998, 25 f. fig. 26. This opinion is accepted by Kienast 1995, 134 n. 220, with thanks to Grewe.

69 For the colossal Rhoikos Temple (see Kyrieleis 1995, 126 f.) the scaffolding had a perimeter of about 315 m. With an approximate height of 20 m and width 5 m its outer volume would be 31 500 m^3. Scaffolding above the Kastro Hill with an average height of 6 m (more than half of each step) and a width of 5 m has the same outer volume, but because of the lower height needs less wooden beams.

The hypothesis of the construction of long scaffolding is a reasonable one, but there is no real evidence yet to justify it. Its proposed existence could be checked in a proper field research project across the surface line with a little systematic archaeological cleaning, looking for some traces of the erection of the scaffolding and such.

The driving

The next serious job was the transposition of the center line to inside the tunnel so as to drive the excavation. The general agreed theory, which was proposed by Kienast and is accepted by other scholars, is that for the north bore the long reference line was used and for the south one the line was defined by a pole at the entrance and the additional help of a vertical shaft about 25 m further within[70]. Kienast notes that the existing shaft is a modern one and was constructed during the discovery of the monument, but he assumes, without strong evidence, that there was another original one at this point or near it[71]. With the new findings, after the dismantling of part of the Archaic lining, which proved that the first part of the tunnel was constructed with the cut-and-cover method, there is no doubt that a shaft at so close a distance to the entrance and just 5 m from the end of the open excavation would be useless for achieving the alignment.

The transposition of the center line in 19th century tunnels was managed with the use of theodolites[72] and in the mines the alignment was performed with the use of compasses[73]. In Eupalinos' time no instrument existed for laying down the center line. The differences at the meeting points of the very short galleries driven from one shaft to the other are proof that the method of extending the short lines of the shafts was not precise at all[74]. The shorter the line that is being extended, the greater the error in its extension[75]. The hypothesis proposed here is that a secure method for an exact transposition of the center line in the tunnel would be a sighting method using a source of light at night at the extreme points B_o and Γ_o of the reference lines of both ends[76]. The point B_o is at the same level with the floor of the tunnel: sighting to it from any point in the interior would give both the direction and the proper level for the driving. On the south side, however, there is a significant difference of level. The proposal here is again the use of high scaffolding, like the observatories of the tunnels of the 19th century[77]. Scaffolding with a height about 45 m could carry at its top a permanent

[70] See Kienast 1995, 136 f. fig. 34 n. 223. 224, with comments for the opinions of the other scholars. See also Grewe 1998, 61 fig. 85.

[71] Kienast 1995, 66 f. fig. 21. Our opinion is that this shaft was used for the transportation of the stone blocks for the construction of the new lining from Ch. 1023 to Ch. 1017 *(fig. 18)*.

[72] Simms 1896, 524: »The tunnel would be ranged from points observed directly from each extremity. In other words, the line of direction being given by the fixation of a couple of terminal points at any visible distance from the ends of the tunnel, the alignment may be obtained either by setting up the instrument, whether a plane transit or a theodolite, over the nearest point. Sighting backwards, reversing, and ranging forward, or by absolutely ranging the line backwards from the fixed points«. See also a very lucid description of the alignment of Mont Cenis tunnel with observations of independent observers in Williams 1883, 175 f.

[73] See the very effective drawing with the compass in Heuchler 1857, 7 pl. 17.

[74] Kienast found that the galleries of the aqueduct before and after the tunnel have a typical S-shape at their meeting points (See Kienast 1995, 71 fig. 22). It is a result of the divergence of the bores, which began from both ends, even although their lengths are only about 12 m.

[75] By contrast, »the farther off [the two points of the line] are the better, as they admit of a more accurate and delicate adjustment by the cross wires of the telescope« (Simms 1896, 525).

[76] Goodfield – Toulmin 1965, 54 proposed also that »a pair of lights was used, like the leading lights in a harbor« for the alignment, but they thought that the southern light was that from the shaft.

[77] A detailed description of the observatory of Saltwood tunnel with a nice engraving is given by Simms 1896, 25 f.

reference point for the driving of the south bore. From the deep darkness of the tunnel these signs would be clearly visible at night, giving the direction and the level of the tunnel[78]. For the first meters of the excavation, probably one or more temporary doors with a small window in their centers were required, so as to localize better the light signal by narrowing its beam.

For reckoning length, the measuring-cord is considered to have been in common use much earlier by the Egyptians[79]. The word *schoinion* is used by Herodotus for other uses, as for pulling or raising objects[80]. Hero describes the proper tensioning and testing of the cord in order that it will not stretch or shrink and to keep its length quite constant[81]. It is questionable if a cord is suitable for measurements of quite long distances, especially with the difficult conditions of tunneling, even if it is properly treated. In the 17th century AD, when the technology for measuring lengths had not yet changed significantly from the Archaic period, the miners extensively used the surveyor's chain[82]. It is quite probable that a predecessor of this chain was used by Eupalinos. A fragment of two connected wires, which was found during the DAI excavation and is presented by Jantzen in the category of ›various‹ findings[83], consists of links very similar to those of a surveyor's chain. One suspects that it belongs to a predecessor of the same.

According to the hypotheses presented above, the driving of the tunnel could proceed with no problem. Eupalinos and his miners knew very well how to face all the excavation problems since at the same time a great quarry was in operation some hundred meters off to the northwest at the side of Katarouga Hill to serve construction activity, which is considered to be more intensive now than in any other town[84]. The main attention should be paid to how the center line was advanced from both portals. The south bore is remarkably straight and generally horizontal for 393 m (Ch. 642.90), at which point the line rotates about 32° eastwards and the excavation stops after 30 m *(fig. 29 a. b)*[85]. The line of the north bore is straight and horizontal up to Ch. 243.5, where the second part of the Archaic lining begins, but it does not lie exactly on the line of that of the south bore. Its southern end is above the line connecting the two end points by about 2.3 m. This discrepancy was considered by Kienast as an error arising because the wooden struts used for the temporary shoring of the unstable rock mass prevented accurate checks in the driving forward[86].

Here we wish to propose another hypothesis. The shaly rock mass begins very near to the north entrance and there was no lining up to Ch. 63.9 for centuries, before the construction of the Roman one. Our experience with the rock mass behind the lining is that it is really unstable especially where ground water flows, but that the necessary protective measures with wooden struts are quite light and would not obstruct the range of the center line. If our hypothesis for the constant light sign near Ayiades is true, the miners would have no difficulty in checking the correct alignment for at least the first 240 m. The diversion eastwards

78 Kienast observed that the zigzag shape of the south bore forms a narrow sighting window which made driving more accurate. See Kienast 1995, 138 f.

79 Clarke – Engelbach 1930, 65 fig. 265; Lewis 2001, 19.

80 The word etymology by Orlandos – Travlos 1986, 244: »πλέγμα εξ ινών σχοίνου«. Hdt. 1, 26: ἐξάψαντες ἐκ τοῦ νηοῦ σχοινίον ἐς τὸ τεῖχος (edition: Godley 1920, 28); Hdt. 5, 85. 86: περιβαλόντας σχοινία ἕλκειν τὰ ἀγάλματα […] οὐ δυναμένους δὲ ἀνασπάσαι ἐκ τῶν βάθρων αὐτὰ οὕτω δὴ περιβαλομένους σχοινία ἕλκειν, ἐς οὗ ἑλκόμενα τὰ ἀγάλματα ἀμφότερα τὠυτὸ ποιῆσαι (edition: Godley 1922, 94).

81 Lewis 2001, 20.

82 It is described in detail and illustrated in Stahl 1687, 343 f. pl. N.19. See also n. 30.

83 Jantzen 2004, 197 table 39. Find no. 1289, which consisted of two twisted wires, was found on the ›bridge‹ at Ch. 905–909 and has a similar form to the surveyor's chain.

84 Kienast 2012/2013, 160 n. 19.

85 Kienast estimates the angle of rotation to have a tangent 2 : 3. Kienast 1995, 166–169 fig. 46 a. We note that the exact definition of an angle with the rock face behind the miners is practically impossible without a transit instrument like a theodolite.

86 Kienast 1995, 170. Grewe agrees with the hypothesis of the error. See Grewe 1998, 65.

of the north bore was not an error. It was intentional, so that the straight north bore would meet the final part of the sloping south one a few meters above the connecting line. It is obvious that the two bores could not meet on the same straight line; the more obvious solution would be to drive the north one angled a little to the east to the waiting inclined final part of the south bore[87]. The definition of this line could be made after the exact location of the desired connecting line with the method defined above: it would require a slight movement of the light signal from the point B_o to another B_o' about 2.65 m westwards *(fig. 29 a. b)*. The new reference line B_oB gives the center line of the north bore (the green line in *fig. 29 c*) so that it meets the inclined part of the south one 5.3 m above the connecting line. It is argued here that this was the initial design of the alignment of the north bore and not an error or confusion. The modification of the initial design took place after Ch. 243.5.

The modification of the driving of the north bore

The second part of the Archaic lining, 20 m in length from C. 243.5, is a segment with an evident rotation eastwards and an inclination of the floor upwards *(fig. 6)*. It follows the V-shaped deviation, which is formed in two segments: one to the west up to the point Σ (Ch. 400) and then to the east between the points Σ and Ξ *(fig. 29)*. This serious modification of the design attracted the interest of Kienast, who believes that the reason was the bad geotechnical conditions[88]. But even after the change the conditions were not improved. As we can see in *figures 6–10*, this triangular deviation is the most vulnerable part of the tunnel, where the most of the interventions took place during the restoration works. So the question, why Eupalinos decided on the modification, remains without a clear answer[89].

More serious a problem than the poor quality of the rock mass at Ch. 243.5 is the water flow, which is considered to be one of the main problems in modern tunneling too[90]. It is reasonable to explain the inclination of the floor of the tunnel upwards as a measure for allowing water to flow off from the forehead[91]. The level of the floor rises up to 2.4 m so that the sight of the north light signal became impossible. The water flow is considerable in this area, but it is present even from Ch. 70 and especially so between Ch. 110 and Ch. 120 *(figs. 4. 5)*.

So what made the modification of the direction inevitable after 170 m? We propose here that the reason would be the loss of the light signal B_o', which had guided the driving for the first 240 m. The humidity in the tunnel had increased significantly by Ch. 243 because of the inadequate ventilation: this made the atmosphere misty and consequently the sign was invisible[92]. The only way to proceed was with measurements of lengths and angles, but the measurement of angles without a transit instrument was very unsafe. A possible way to ensure meeting the south section would be to continue driving eastwards following the direction the lining is taking (see the upper part of *fig. 6*). The extension of this line intersects the extension of the inclined segment of the south cutting about 24 m above the present connecting line (magenta line in *fig. 29 c*). But this solution, unsupported by any reference line, would direct the tunnel a significantly greater distance to the east. It would not have

[87] The other possible solutions with a T-shaped end of the south bore or with two inclined parts presented by Kienast 1995, 141 fig. 36 seem not to be alternatives considered by Eupalinos.

[88] Kienast 1995, 142; Kienast 2005, 46.

[89] These unanswered questions are presented in Zambas et al. 2016, 72–74.

[90] See generally in Prelini 1912, 7 f. and many cases in Simms 1896, 21 f. 60. 85. 198. 204. 417.

[91] Kienast 1995, 52 fig. 15.

[92] For the influence of humidity in the working conditions, see Lauchli 1915, 145–149.

been an intelligent solution to try to approach the meeting point with excavation from both sides[93].

Various detailed explanations for the design of this deviation exist[94]. It is very probable that the geometric design of the deviation in relation with the whole layout was mapped out in full scale on a horizontal plane on one of the extensive beaches near the ancient city[95]. In such a way Eupalinos could have obtained very exact full-scale measurements of the lengths and the angles, but the great problem was still to transpose these angles into the tunnel, because we can measure there exactly the abscissas, but not at all the ordinates[96]. After the excavation towards the direction of one side of the triangle, in which the difficulties encountered are obvious from its zigzag shape *(figs. 6. 7. 29)*, its center line could be defined accurately. At the next side of the triangle the direction of the excavation could not be determined in the same way, as the rock behind the miners did not permit the definition of a reference line. The solution was an approximate one. In order to avoid missing the target by simply driving the tunnel eastwards, Eupalinos decided, remarkably, to rotate the center line on the horizontal plane to the west and then again to return to the eastward line so as to approach the south bore. The evaluation of the desired real route would be made only after the completion of this excavation by checking distances and angles with the auxiliary center line as laid out on the sea shore. With measurements of the lengths and by drawings of the angles he could estimate the position of the third edge of the triangle a little after the point Ξ *(fig. 29)*. He had already modified the system for the chainages in order to take into account the enlargement of the route as was ably discovered by Kienast[97]. The new system begins with the letter K at Ch. 237.50 and the last letter of the old was finished with Λ 2.5 m after it (left corner in *fig. 29 c*)[98].

It seems that the segment ΞΠ follows the modified direction, being pursued already before the V-shaped deviation. The last curvilinear segment of the north bore, with its shape of a hook, is obviously not a geometric construction. It begins about 30 m before the end of the south bore and has a length of 43.9 m. A reasonable assumption to account for this is that as well as the calculations for the remaining route, the sound from the tools of the southern crew of miners helped co-ordinate the final breakthrough[99]. The significant upwards slope of the last 27 m before the meeting point resulted in a 2.5 m difference between the roofs of the two bores *(figs. 11. 12)*[100]. A similar, but lower, difference exists between the gallery coming from the spring with the tunnel in Ch. 10 *(fig. 2)*. We are of the opinion that in both cases the miners followed the strata of the rock in order to avoid intersecting with the roof of the waiting bore at the same or a lower level. They were probably afraid that in these cases the sudden release of stresses at the end of the proceeding bore would cause a collapse.

93 Grewe compares this procedure to two people attempting to thread the eye of the needle when one has the needle and the other the thread. Grewe 1998, 63 n. 122.

94 Tempelis 1991b, 22–30; Kienast 1995, 142–149; Grewe 1998, 64–69. Grewe supported the opinion that the meeting point, according to the initial design, should be at the middle of the connecting line. This is a hypothesis which cannot be excluded.

95 The scaffolding on the hillsides would have been dismantled a while ago, because after the location of the center line on the surface of the ground it served no further purpose at all.

96 This is a serious disadvantage for the implementation of the raster method, which was proposed by Grewe 1998, 66–69 fig. 89.

97 Kienast 1995, 132–134. The successful design of the triangular deviation is correlated by Kappel 1999, 93–98 with the inscription ΠΑΡΑΔΕΓΜΑ and the distance between the two vertical lines before and after it. Kienast 2005, 54 accepted this opinion. Another interpretation was given for the inscription by Wesenberg 2007.

98 Kienast 1995, 152–154.

99 This is noted by Kienast 1995, 171.

100 Kienast 1995, 56. 148 fig. 17.

The ventilation of the tunnel during excavation

An odd omission by all the scholars who have dealt with the tunnel of Eupalinos is the lack of any examination of the problem of ventilation during the excavation. In the tunnels constructed with the qanat method the distances between the vertical shafts together with the depth of them were defined in such a way as to ensure their ventilation. For the shafts of the ancient Greek mines and especially for the mines of Laurion the need for proper ventilation is reported by the early researchers. Édouard Ardaillon and André Cordella emphasized that the ventilation was made either by opening two shafts in parallel or by the partition of a shaft in two with a wooden insertion: the circulation of the air was achieved by lighting a fire at the bottom of one of them[101]. The double shaft method is supported by Morin and others with additional documentation and the monitoring of the deep shafts of Laurion[102]. The essential role of the proper ventilation of mines was examined extensively by Georgius Agricola in the Fifth chapter of his important book *De re metallica*. He writes: »Air, indeed, becomes stagnant both in tunnels and in shafts; in a deep shaft, if it be by itself, this occurs if it is neither reached by a tunnel nor connected by a drift with another shaft; this occurs in a tunnel if it has been driven too far into a mountain and no shaft has yet been sunk deep enough to meet it; in neither case can the air move or circulate. For this reason the vapours become heavy and resemble mist, and they smell of mouldiness, like a vault or some underground chamber which has been completely closed for many years. This suffices to prevent miners from continuing their work«; he describes in detail the machines for the ventilation of the mines with instructive illustrations[103]. The necessity of proper ventilation is documented by recent studies both with monitoring and mathematical investigations, which proved that after 50 m of excavation the air quality is inadequate for the miners[104]. The above observations lead to the conclusion that the tunnel of Eupalinos could never have been constructed without a provision for effective ventilation during the excavation works.

The monk Synesios was the first to refer to the problem of the ventilation in his book of 1899[105]. He rejects Guérin's theory that Eupalinos made a mistake in the level of the tunnel, making it higher than required[106]. He argued in a general way that the difference between the level of the tunnel and the level of the spring and the dimensions of the section of the tunnel all had to do with ensuring the ventilation of the excavation, without which the miners could not breathe and no flame could be lit to see by. Carl Curtius believed the section of the tunnel had to do with its ventilation in his unpublished diary[107]. Kienast, who gives this information, mentions only that the conditions of the work were »with stifling and smoky air, and with increasing depth also increasing temperatures« with no other reference to the problem of ventilation[108].

We will here investigate a possible function that the trench of the tunnel may have had with regard to the ventilation of the excavation. As we have noted above, Kienast found that at the first stage of the excavation of the tunnel, the trench at its east side was dug together with it, and that this trench was deepened in a second stage. He also noted that the gallery coming from the spring over its last 185 m before meeting the tunnel, i.e. from the third shaft before it (point HK13 in *fig. 29 b*), has a remarkable height: it is clear that it was deepened later too[109]. He did not accept Guérin's opinion of a mistake in leveling between the spring

101 Ardaillon 1897, 49–53. Conophagos 2004, 202 was of the opinion that only the division of the shaft was needed to promote the ventilation.

102 Morin et al. 2012, 15–17.

103 Agricola 1556, 121.

104 Florsch et al. 2002, 62.

105 Synesios 1899, 117 f.

106 Guérin 1856, 318.

107 Kienast 1995, 97 n. 183.

108 Kienast 1995, 96.

109 Kienast 2005, 184.

Fig. 31. Notches on the edge of the floor and on the wall above a bridge between Ch. 765 and Ch. 770

and the north portal of the tunnel. Rather, based mainly on indications from the artificial formation of the rock in the spring and the traces on the side of the trench, he presented the explanation that after the completion of the tunnel Eupalinos realized that there had been a subsiding of the spring of about 3 m and so he was forced to deepen the excavation[110]. It is unlikely perhaps, but not impossible, that the spring subsided so severely in the few years needed for the construction of the tunnel, while for the next millennium the spring remained stable. Another geotechnical explanation for the higher location of the tunnel was given by Renate Tölle-Kastenbein. She proposed that the initial trench was designed to relieve stresses in the ground during excavation to safeguard conditions in the main tunnel, but this explanation is not justified by the structural aspect[111].

Our opinion is that the excavation of the first phase of the trench would provide a solution for the ventilation of the forehead of the tunnel, if it were covered with a wooden floor covered with a thin layer of clay. This hypothesis is illustrated in *figure 30* which was drawn by Gerasimos Thomas according to the guidelines of the author. The trench was designed and constructed to serve the ventilation of the tunnel in a similar way with the parallel vertical shafts of the mines of Laurion. Albeit now set horizontally. The regular notches both on the east wall of the tunnel and on the edge of the floor are evidence for wooden beams, which bridged the gap of the trench. Kienast is of the opinion that these notches are made in Byzantine times for the safety of the refugees, who lived in the tunnel[112], but the treatment of the notches is quite well-done and seems to be Archaic. Pairs of notches are found also in some parts were there was no open trench, as between Ch. 765 and Ch. 770 and there was no risk for the later inhabitants *(figs. 14. 31)*. A large number of the notches at the edge of the floor were lost because the edge collapsed. There was not always a necessity of a notch on the other, east side of the tunnel, because a beam could be wedged on the lower part of the surface, which usually projects here. Our proposal, then, is that the beams and a wooden floor were constructed over the open trench and used during the construction of the tunnel.

Ventilation in mines occurs naturally in deep shafts because of the difference of the temperature between the rock at the surface and that at the bottom. For parallel and communicating shafts a difference of the temperature between the ends of the two shafts of about 1.5 °C is enough to activate the air flow from the entrance of the one to the entrance of the

[110] Kienast 2005, 26 f. fig. 18; in detail: Kienast 1995, 99 f. He notes though that the process of the works can only be guessed.

[111] Tölle-Kastenbein 1991, 42 f.; Tölle-Kastenbein 1994, 37 fig. 30. She refers to the opinion of H. J. Palm, who was president of the Deutscher Markscheider Verein 1987–1989 (Deutschmann 2015, 8), but he has not published anything about the tunnel of Eupalinos.

[112] Kienast 1995, 184. The presence of Byzantine finds between collapsed wooden pieces during the excavation does not exclude that another wooden floor existed in the Archaic times.

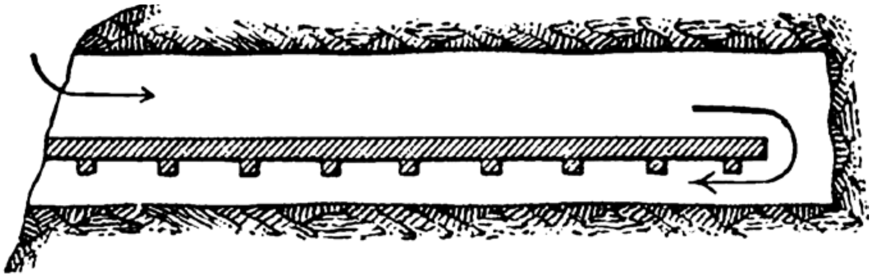


Fig. 32. Natural ventilation of a heading, early 20th c. illustration

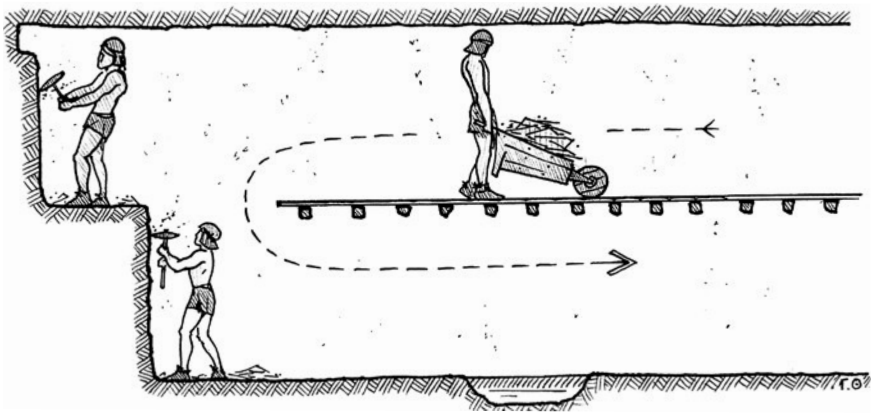


Fig. 33. Illustration of the excavation of the tunnel of Eupalinos with natural ventilation

other, because the air flow is not caused by the difference in specific weights of the interconnected air columns, but by the conversion of heat into mechanical energy[113]. In the case of the tunnel of Eupalinos we have not vertical shafts, but a horizontal heading and a trench to one side of it, which were separated with the wooden floor sealed with clay above the trench. This system, with a partition of a heading with a wooden brattice, is reported as suitable to achieve natural ventilation in the classic book of Robert Wabner for the ventilation of mines *(fig. 32)*[114]. The light-sources necessary for the works and the body heat generated by the activities of the workers at the forehead of the tunnel must have produced higher temperatures there than in the trench.

If the level of the tunnel was designed to be 3 m lower and the water pipes in the tunnel were near its floor, there would be no way to excavate a trench necessary for the ventilation of the excavation works. That is the interpretation given to explain the form of the high final part of the gallery from the spring: it provides, via the vertical shafts, a second entrance for the air flow at a level appropriate for efficient ventilation. The conclusion is that the level of the tunnel was defined ingeniously in Eupalinos' initial design, so that the trench at its east side would ensure the natural ventilation of the excavation *(fig. 33)*[115]. The trench was excavated at the same time with the tunnel and it was separated by a wooden floor, which was

113 Tien 1999, 147 figs. 8-2. 8-3.

114 Wabner 1903, 105 pl. 8 fig. 51. He writes: »Ventilating currents in headings. The same causes that disturb the equilibrium of the air in shafts also operate in headings, though only to a relatively feeble extent […]. As in shafts, the effect may be increased by separating the two currents with a brattice (see Figs. 51 and 52). This partition may be placed either vertically or horizontally, and must be arranged in such a manner as to present a minimum of obstruction to the traffic of the heading, namely, at the side or near the floor. In sloping galleries the conditions are similar to those in shaft«.

115 The direction of the air flow is indicated according to Wabner's drawing, but it could be the opposite too. This was the opinion of V. Spiliadis, Mechanical Engineer, when he saw the drawing.

also very useful for the circulation of the workers and the transportation of the materials, as was discovered during the restoration works. It is probable that pits here and there in the floor of the trench were used as sinks for the gathering of the water flowing from the rock mass, to be removed with baskets *(fig. 33)*.

After the successful breakthrough the ventilation of the tunnel became perfect, as it is nowadays. In some parts the trench was deepened and in others galleries were excavated below it. The unexcavated bridges above the galleries act as horizontal supports and buttresses for the common east side of the tunnel and the trench: together these have a great height and are vulnerable in the areas where the quality of the rock mass is poor.

Aspects of the construction

In the terminology devised for modern tunneling practice, the tunnel of Eupalinos is a top heading[116]. Like some of the tunnels of the 19th century AD, it was excavated as an advanced gallery and extended downwards at one side. The main difference from the tunnels of the 19th century for the railways was that they were extended in all directions. This is only reasonable because in the railway tunnels the heading has to be significantly enlarged, while in an aqueduct only a channel for the water pipes had to be formed. The dimensions of the tunnel of Eupalinos are a little larger than those of the smaller headings of the Victorian tunnels[117]. Of course it was excavated only by hand tools, with no mechanical assistance. For modern engineers such a work seems very hard and time consuming, but if we compare it with other similar works of antiquity, as the quarrying of building stones and the opening of mines, we can say that from the point of view of labor it is not something unusual. The Archaic quarries on the hillside opposite the north portal have a total length of passageways between the columns and the sides of the rock mass of about 850 m, and are much more in height. The total volume of the extracted material[118] was about 38 000 m^3, which is four times the quantity of rock excavated for the aqueduct[119]. So the knowledge and the experience from the quarries were valuable for the tunnel.

The main tools were not the pointed chisel / punch and the hammer, but most probably the pick, which is more productive for quarrying stones[120]. The long curvilinear traces in many places at the sides of the tunnel are clear evidence of its use[121]. Undoubtedly two miners worked at the forehead, but we think each tackled a width much less than that which is indicated by the traces on the ends of each bore[122]. The two drifts at the forehead must have had a width of about 50 cm, similar to that of the channels used for the quarrying of stones *(fig. 30)*[123]. The removal of the material between the two positions, at a width of about 80 cm,

[116] Simms 1896, 191 distinguishes two systems of driving tunnels: the bottom heading (the English or the German system) and the top heading (Belgian or French system). In the first the heading is opened and driven at the level of the floor of the tunnel, which is then completed upwards and laterally, while in the second excavation starts with the upper part of the tunnel and is extended downwards.

[117] The method for the opening of driftways (small headings) is described by K. Clark in Simms 1896, 191–197, who repeats what A Civil Engineer 1868, 19–21 described in detail.

[118] Kienast 2012/2013, 159. The estimation of the length is a rough calculation based on the general drawing in Kienast 2012/2013, 147 fig. 4.

[119] It is about 8000 m^3 according to Kienast 2005, 28.

[120] Koukouvou 2012, 189–205 has investigated the tools of the ancient quarrymen. She agrees with Bessac 1988, 42; Bessac 1991, 103 f. on the use of the quarrying pick. Korres 1993, 22 f. shows the same picks in his illustration. The plaque of the 7th century B.C. from Corinth with the miner at work shows a similar tool. See Robinson 2011, 162 fig. 91.

[121] Very characteristic examples of these long curvilinear traces exist in Ch. 561 and Ch. 870.

[122] Kienast 1995, 57 f. fig. 17. See also *figs. 10. 11* here.

[123] Korres 1993, 74.

was quite easy and fast because of the schist material. With the opening of a hole at the top (or at the bottom), the whole intervening volume could be removed quickly in pieces by splitting the layers by a lever or by steel wedges *(fig. 30)*.

It is worth noting that the dimensions of the tunnel are such as to secure the optimum rate of progress for the excavation. Two miners can work unimpeded in the width of 1.80 m to open two driftways and then to remove easily the intermediate rock mass. If the width was considerably less (e.g. about 1.20 m), that would be impossible. The height of 1.80 m is also proper for someone working with the pick *(fig. 30)*. The typical form of the section of the tunnel, which is a truncated barrel with horizontal base and an inclined upper side, is a product of the way of excavation: the curved sides are produced because of the way in which the miner works with the pick swinging downwards. The roof is formed by the inclined layer of the rock. The non-linear plan of the tunnel is also formed because the face of the rock beside the miner prevents him from working exactly on a straight line with it, but rather he tends to work a little inside it, so producing a curve away from it as he advances *(fig. 30)*.

Korres estimates, with detailed calculations, that the time needed for the opening of a channel in Pentelic marble with a width of 0.50 m, length 2.50 m and a depth of 1.00 m was 54 hours, or 22 hours per m of length[124]. The rock of the tunnel is softer than marble[125], but digging is more difficult because it was made in front of the workman and not from above as in the quarries, and in more difficult conditions. For a driftway at the forehead of the tunnel of 1.80 m height, we can make a rough and conservative estimation of a rate of 0.5 m per 24 hours[126]. At this rate, the south bore must have been finished in two and a half years[127]. The longer north bore had in its first 240 m a very much softer rock to go through and despite the necessary shoring, the work will have proceeded faster. Taking into account the modification of the route, the water flow situation and all the difficulties of it being the first attempt at such a task, we estimate that the total time for the construction of the tunnel did not exceed four years.

CONCLUSION

The more we examine the tunnel of the Architekton[128] Eupalinos, the more we must admire this great historical innovation in working below ground. The proposals which were presented above include estimations and hypotheses, soundly based wherever feasible on the further documentation obtained during the restoration study and the works, but with no undoubted proof. They are presented here as a contribution to the technical discussion, which is of an interdisciplinary nature, as an incentive for further research. Eupalinos proved with his design and the construction of the tunnel that »the greatest ideas are the

124 Korres 1991, 86.

125 The hardness of the rock mass of the tunnel was measured with the Schmidt hammer method and was found to vary from 10 to 40 for the north bore and from 30 to 50 for the south one (Edafos S.A. 2009, 33 fig. A.1).

126 Kienast estimates a much lower rate for the excavation, at 12–15 cm per 24 hours (Kienast 1995, 94 f. n. 177) and 8 years before the meeting of the two work gangs (Kienast 2005, 22).

127 The headings of Mont Cenis tunnel with a section of 3 × 3 m from 1857 to 1862 were opened with hand-driven drills and explosives: they advanced at a rate 0.65 m per day from one end and 1.12 m per day from the other. Simms 1896, 246 f. 252 f.

128 The term ἀρχιτέκτων is used for the first time by Herodotus, as is emphasized by Matthaiou 2016, 99. Coulton 1977, 16 clarified that »Until the development of the theoretical mechanics in the late fourth and early third centuries, there was no distinct concept of engineer as opposed to architects«. See the relevant comments by Kienast 1995, 175 n. 257.

simplest«[129]. A long straight line was defined from two points between Ayiades and the seashore. The points at which this line intersects the sides of Kastro Hill define the two portals of the tunnel. The line which connected these points was located on the ground surface with a help of long wooden scaffolding set above the hillsides. The tunnel was excavated having as guides lights set up at Ayiades and at the top of a wooden tower by the seashore. The level of the tunnel was set so that a trench at its east side could be excavated together with it. The works proceeded from both portals at the same time; the trench was covered with wooden floor so that ventilation of the forehead was ensured naturally by the air flow through them, stimulated by the difference of the temperature between the entrances and the forehead. When the sign of Ayiades was no longer visible to the miners of the north bore, because of the high humidity inside the tunnel, Eupalinos modified the design and produced a deviation by approximation, which he must have continuously checked on a reproduction laid out on a level site (like the seashore), and successfully achieved an accurate breakthrough. This simple solution of an unpredicted problem is as much a mark of his genius as is the overall design of the project. The time for the cutting of the tunnel was less than four years. The design and the construction of the tunnel is a unique historical example of ingenious engineering.

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[129] This is a quote by William Golding (1911–1993), British novelist, poet and playwright best known for his 1954 novel *Lord of the Flies*.

Sources of illustrations: *Fig. 1:* National Cadastre and Mapping Agency S.A.; survey of the tunnel after Tokmakides 2009; other ancient remains after Kienast 2005, 17 fig. 8. – *Figs. 2–18:* C. Zambas, G. Thomas and E. Doudoumi. – *Figs. 19. 23. 24. 25. 27 b; 28. 31:* C. Zambas. – *Figs. 20. 21:* M. Psallida. – *Fig. 22:* X. Briolas. – *Fig. 26:* C. Zambas, based on documentation by X. Briolas. – *Fig. 27 a:* C. Zambas, based on documentation by V. Sarris and A. Mastora. – *Fig. 29:* C. Zambas, based on survey by K. and P. Tokmakides (Tokmakides 2009). – *Fig. 30. 33:* G. Thomas, based on sketches by C. Zambas. – *Fig. 32:* Wabner 1903, pl. 8 fig. 51.

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