The geology of Eupalinos Aqueduct, Samos Island, Greece

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ABSTRACT: Eupalinos Aqueduct, built circa 550 BC, is not only a unique ancient monument and an astonishing pioneering achievement of engineering, but also an outstanding evidence of the timeless interaction between humankind and geological formations. The famous tunnel, 1036m long, is bored through the hill of ‘Kastro’ and is preserved in a good condition. The tunnel suffers locally from geological instabilities of varying severity. A detailed geological study was undertaken as part of a multi-disciplinary design campaign to protect and restore the monument. Main aspects of the geological conditions characterizing the aqueduct were studied, such as lithostratigraphy, tectonic structure and groundwater conditions, in order to provide data for the design of the rehabilitation measures. The paper focuses on the geological structure of the monument and on the relation between the structure and the engineering geological conditions. Geological mapping was prepared in two scales, one detailed (1:50 – 1:25) for the interior of the main tunnel and one broader (1:500) for the surface mapping of the whole aqueduct. A longitudinal section was prepared along the aqueduct combining the tunnel and the surface mappings. Along the northern part of the tunnel, where the presence of ancient Greek and Roman lining in the tunnel does not permit the direct observation of the rockmass for many meters, this correlation was assisted by geophysical investigations.

Keywords: Eupalinos, Tunnel, Geology, Monuments, Samos

1 Geological studies

The geological study of Eupalinos Aqueduct, together with the geotechnical design, was part of a multi-discipline design campaign to protect and restore the monument. The whole project also included architectural, structural, survey, geophysical and electro-mechanical design works. The project was planned, organized and supervised by Egnatia Odos S.A. in cooperation with the Greek Ministry of Culture and the Prefecture of Samos and it was financed by the Greek Ministry of Public Works. Agistalis \& Kouroumli Arend (this Volume) provide a short description of the project, as well as an outline of the monument.

The purpose of the geological study was to investigate, to record and to analyze the geological conditions characterising the ancient structure, both on the surface and in the interior of the underground section, in order to determine its engineering geological model. One of the main scopes of the study was also to identify and describe, in terms of qualitative and quantitative detail, the potentially unstable geological structures along the underground section of the aqueduct. In order to feed the geotechnical – restoration design with precise data about the mechanism, the volume and the possibility of the potential failures within the Eupalinos tunnel, a codified system of engineering geological hazard ranking was established and customized according to the requirements of the particular project.
The geological works included mainly: (i) Geological – engineering geological mapping and hazard ranking of the tunnel (1036m), scale 1:50. The base map was an unfolded projection of the periphery of the tunnel in plan view, (ii) 38 geological cross sections, scale 1:25 and 3 segments of longitudinal section, scale 1:50, in significant positions in the tunnel, (iii) Collection of more than 1200 tectonic measurements and construction of 25 microtectonic diagrams in locations of instabilities, (iv) On-surface geological mapping along the aqueduct area (~2.5km), scale 1:500, (v) Geological section 1573m long, scale 1:500, which combines underground and surface data, (vi) 4 Mineral, 6 Petrographic, 6 Micro-paleontological and 5 Groundwater Analyses, in order to determine the nature and stratigraphic relation of the encountered materials and the groundwater conditions.

![Figure 1. Geomorphological map of Samos. Gray: Alpine Basement, Orange: Neogene basins, Yellow: Quaternary deposition. Arrow: Location of the study area. Base map: Google-earth. Geological information: Theodoropoulos (1979), simplified.](image)

## 2 Eupalinos aqueduct within the geological environment of Samos

### 2.1 General geological background

The geological history of Samos involves alpine nappe-piling, development of neogene molassic basins accompanied by volcanic activity, and an ongoing post-Miocene sedimentation and tectonism. The pre-Neogene basement is structured by a successive series of nappes, consisting mainly of metamorphic and secondarily of non-metamorphic rocks (Papanikolaou, 1979, Ring et al., 1999). It forms three zones of high morphological relief which are extended throughout the island, from the northern coasts to the southern ones, where the central one belongs to the Ambelos Mountain (Figure 1). At both sides of the central ridge two molassic-type basins of Mio-Pliocene age have developed (Karlovasi Basin in the west and Mytilinii basin in the east). They are characterized by lower and smoother morphology and they are filled with fluvial and lacustrine sediments. Volcanic activity along the faults that bound the basins with the Ambelos basement zone has also generated basaltic and tuff interlayers. Quaternary coastal, alluvial deposits and scree deposits have unconformably deposited on the previous formations. The most extensive area of quaternary deposition is Hora plain (Figure 1).

Samos is characterized by seismic activity and by the presence of onshore and offshore active and possibly active faults (Chatzipetrou et al., 2012), which are related to the present extensional tectonic regime. The seismicity of the area surrounding Samos is well documented by instrumental and historical seismic data. Geological – morphological and geoarcheological indicators, summarized in Stiros et al. (2000), introduce the influence of active tectonism in the recent morphological development of the Island.
2.2 Hora and Pythagorion Formations of Mytilinii basin

Mytilinii basin is filled by two fluvial-lacustrine depositional cycles (Weidmann et al., 1984, Meissner, 1976), which are separated by a disconformity (dated 8.5-9.0 Ma): (i) the overlying, Upper Miocene – Pliocene(? ) cycle, which bears the famous mammalian fauna of Samos, and (ii) the lower cycle of Middle – Upper Miocene. The aqueduct is constructed within the lower cycle Pythagorion and Hora formations (Weidmann et al., 1984, Meissner, 1995). Pythagorion formation (thickness 95-200 m) lies conformably on the basal conglomerate of Mytilinii basin and consists of shallow lacustrine, mainly thick-bedded limestones, with rare and thin tuffaceous interlayers (Weidmann et al., 1984). Towards the west, they interfinger with paludal horizons consisting of bituminous limestones and organic-rich clastic horizons. Basaltic and tuff intercalations are derived from the westernmost border of the basin, where the volcanic products are thicker, but they gradually become thinner eastwards (1-2 m and less). A main volcanic event, marked by basaltic flows dated ~11 Ma by Weidmann et al. (1984), is considered to be the boundary between the Pythagorion and Hora formations. This layer is not present along the whole basin. The overlying Hora formation (thickness 50-400 m) represents a deeper lacustrine depositional environment consisting of alternations between thin-bedded, thick-bedded limestones, marls and shales. Tuffaceous interlayers are also present. Syn-depositional slumping characterizes the soft or the border between the soft and the hard horizons. The Pythagorion and Hora formations have undergone diagenetic processes, mainly silicification, which is described thoroughly in Stamatakis et al. (1989) and Stamatakis (1990). Diagenetic transformations in the Hora formation are more complex due to its heterogeneity.
3 Morphological setting of the aqueduct

The aqueduct is an underground channel about 2.5 km long, 0.6-0.7 m wide, constructed to convey water from the spring of Aghiades to the ancient town of Samos, where the modern Pythagorion town is located. In order to achieve that, it was bored obliquely through the Kastro hill in a NNW-SSE direction (Figure 2). Kastro hill is part of the southern hill range, one of a series of NW-SE-directed hill ranges which characterize the interior of Mytilinii basin. The direction of the hill range is controlled by the dominant trend of strata of Pythagorion and Hora formations (Fig. 2).

The maximum altitude of Kastro Hill is +237.9 m. The general dip direction of the bedding towards NNE with a dip angle of 20° gives the hill an asymmetric shape (Fig. 3). The north slope of the hill more or less coincides with strata and is smoother (15° to 25°) than the south slope (25° to 30°), which is transverse to the dip direction (Fig. 4). On the top of the hill a few deep karstic holes penetrate the limestone.

The hill is bordered on its NNE side by the narrow valley of Aghiades which has the same NW-SE arrangement as the hill range. The valley is covered by alluvial deposits, which also cover the unconformity between the underlying Hora Formation and the overlying Mitilinii Formation. The Pythagorion fault zone borders the SSW side of the hill. In its hanging wall lies Hora plain, which is covered by alluvial and coastal deposits (Fig. 2). The small Glyfada lake is also developed in the plain. To the west, Kastro hill is divided from the rest of the hill range and particularly from the neighboring ‘Katarouga’ hill, by a gorge, through which Aghiades valley is drained towards the Hora plain. Katarouga hill contains ancient quarries, which were developed along certain limestone horizons.

The aqueduct is divided into three distinct segments (Fig. 2). The first is the ‘spring’ segment, which begins at Aghiades spring, where a cistern was excavated in limestone. Afterwards it follows the smooth morphology along two streams. For 740 m it was excavated as an open trench, covered afterwards. For the next 150 m, along which the overburden becomes higher, it was excavated underground applying the ‘qanat’ method (vertical shafts were bored every 30-50 m, used for the interconnection of the in-between galleries). Along the path of the latter segment, limited rock sliding affects the slope.

The second is the tunnel segment -1036 m long- along which the aqueduct penetrates the higher part of Kastro hill. Its entrance (north portal) is located on the slopes of the same stream. The main tunnel, approximately 1.8 m x 1.8 m, was bored from both sides (‘amphistomon’ according to the term of Herodotus) almost horizontally. The ‘meeting point’ of the two excavations (Fig. 5), ~610 m from the north portal, is located below the highest altitude along the tunnel course, +225 m (but not below the crest of the hill, which is +237.9 m) and consequently has the highest overburden, 170 m. The water conveying trench usually follows the east side of the tunnel. Its depth increases towards the south portal (exit) of the tunnel from 4 to 9 m below the floor level of the tunnel, in order to retain a hydraulic gradient (0.3-0.45%) along its course.

The third is the ‘urban’ segment of the aqueduct, along which the channel turns eastwards directed towards the ancient town of Samos. It follows the contours of the slope which is covered by scree deposits. It is inferred to have reached the town center or probably the port. Approximately 500 m have been traced so far, along which the trench was excavated using the ‘qanat’ method.
4 Stratigraphic and engineering geological units

The stratigraphy is divided in three categories: Quaternary – recent formations, Molassic Formations and Tectonic formations.

4.1 Quaternary – recent formations

They unconformably cover the older formations and appear in lower relief areas at both sides of Kastro hill.

(w) Man-made deposits were derived by the deposition of excavation products during the construction of the tunnel, consisting mainly of limestone fragments and marly material. They are partly mixed with colluvial deposits and products of rock failures. They are located below both portals of the tunnel. Thickness: up to some meters.

(co) Colluvial deposits consisting of limestone fragments and blocks and fine-grained material, marly or terra rossa. They are located mainly along the south slope of Kastro. Estimated thickness: 5-20m.

(r) River axis and river terrace deposits. Loose sand and gravels. Thickness: <5m.

(al) Plain areas deposits. Alluvial deposits consisting of sandy – silty – clayey mixtures with gravels. They cover Aghiades plain.

Figure 6. Example of engineering geological mapping of the tunnel on the unfolded projection of the periphery of the tunnel in plan view.

4.2 Molassic formations

4.2.1 Lithofacies – Engineering Geological Units

Both Pythagorion and Hora formations are formed by a sequence of six alternating lithofacies which correspond to units of similar engineering geological behavior. They are presented in order of descending behavior and increasing geotechnical problems. They were mapped in the tunnel, whereas an example of the map is shown in Figure 6. In Table 1 an outline is provided of their engineering geological characteristics and potential geotechnical problems.
### Table 1. Engineering geological informational table of the lithofacies occurring in Eupalinos aqueduct

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<td>Strata Unit</td>
<td>Pythagorian &amp; Hora</td>
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<td>Pythagorian &amp; Hora</td>
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<td>Hora (mainly)</td>
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<td>Strength</td>
<td>Strong to Medium</td>
<td>Strong to Medium</td>
<td>Medium</td>
<td>Medium to Weak</td>
<td>Medium to Very weak</td>
<td>Very weak</td>
<td>Strong to Very weak</td>
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<td>RGD range</td>
<td>70-100%</td>
<td>70-100%</td>
<td>25-70%</td>
<td>10-30%</td>
<td>0-20%</td>
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<td>GSI range</td>
<td>60-70</td>
<td>50-60</td>
<td>35-45</td>
<td>30-40</td>
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<td>15-25</td>
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<tr>
<td>Tectonism</td>
<td>Small</td>
<td>Small – Medium</td>
<td>Medium – Intense</td>
<td>Medium – Intense</td>
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<tr>
<td>Inhomogeneity</td>
<td>Small</td>
<td>Small – medium</td>
<td>Medium</td>
<td>Medium – High</td>
<td>High</td>
<td>High</td>
<td>Small – High</td>
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<tr>
<td>Anisotropy</td>
<td>Small</td>
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<td>High</td>
<td>Very high</td>
<td>Very high</td>
<td>Very high</td>
<td>Small</td>
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<tr>
<td>Susceptibility to weathering</td>
<td>Small</td>
<td>Small – Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Very high</td>
<td>Small – High</td>
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<td>Permeability</td>
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<td>Medium – High</td>
<td>High</td>
<td>Very small</td>
<td>Very small</td>
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<td>Failure Hazard</td>
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<td>Small – High</td>
<td>Very high</td>
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<td>Common Failures</td>
<td>Local gravel and small block falls along highly fractured zones</td>
<td>Local gravel, small block &amp; rarely platy fragment falls along highly fractured zones</td>
<td>Gravel and block falls along highly fractured zones</td>
<td>Platy fragment falls and detachments of platy rock mass</td>
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<td>Gravel, block of gravels and block falls</td>
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</table>
a. Massive and thick-bedded limestone. Whitish, grayish to yellowish limestone, marly limestone and travertine, massive or thick-bedded. Frequent internal brecciation or porcelaneous appearance.

b. Medium-bedded limestone. Similar to the massive limestone, but showing prominent layering every 5 to 50cm and more frequent separation between the layers.

c. Brecciated limestone. Massive or medium-bedded limestone showing intense brecciation and usually moderately to well interlocked between the blocks and fragments.

d. Platy limestone. Whitish, grayish to yellowish limestone and marly limestone, often chert-like, showing well expressed and close (0.5-8cm) layering, frequently separated by thin horizons of yellowish, whitish or greenish stiff or soft marls.

e. Platy limestone and marls. Frequent alternations between platy marly limestones and stiff to soft fissile clayey and silty marls of yellowish, whitish or greenish color.

f. Shales and marls. Frequent alternations between soily to stiff fissile clayey and silty marls and green clay shales with intercalations of platy limestones.

By the observation of Table 1, the hazard of failure increases when:

(i) the separation along the bedding becomes closer, leading to lower tensile strength of the bedding plains and consequently to collapses at the roof of the tunnel,

(ii) the participation of weak horizons of clayey shales and soft marls increases. They reduce dramatically the shear strength of the bedding, even if they are mm-thin, especially because they are usually wet and pre-sheared. They lead to collapses and sliding on the tunnel roof and walls.

(iii) the fracturing of the rocks increases along faults and large joints.

On the above factors, the possibility and volume of instability in the tunnel is also controlled by some other factors, such as the orientation of strata and discontinuities in relation to the tunnel axis, the presence of water, the thickness of the alternating lithofacies, the thickness of the overburden and the degree of stabilization of the roof and walls by calcite deposition.

4.2.2 Stratigraphic formations

In order to demonstrate the large scale stratigraphic structure of the area, the Hora and Pythagorion formations have been distinguished in the following units, according to the participation of the lithofacies (a)-(f) and the mode of succession between them. Every unit represents a stratigraphic package that has considerable lateral extent and thickness. Although the classification was done for engineering geological purposes, is in general agreement with the stratigraphic columns of Weidmann et al. (1984) and Meissner (1976).

**A. Hora Formation (Middle - Upper. Miocene)**

(Ho1) Platy limestones. Lithofacies (d). Thickness: ~50m.

(Ho2) Upper platy limestones with intercalations of marls. Lithofacies (e). Transitional between units Ho1 and Ho2. Thickness: 25-30m.

(Ho3) Shaly – thinly bedded alternations. A weak and heterogeneous unit, consisting of alternations between platy limestones, marls and clay shales. Lithofacies (e) and (f). Thickness: ~55m.

(Ho4) Massive limestones in alternation with shales and marls. Benches of massive limestones, separated by clay shales and marls. Lithofacies (a), (c) and (f). Thickness: ~50m.

(Ho5) Lower platy limestones with intercalations of marls. Lithofacies (e).

(Ho6) Massive limestones. Lithofacies (e) and (c).

Units (Ho5) and (Ho6) alternate in 10-60m thick horizons to form the lower part of the Hora formation, which has a total thickness of 100-150m in the area.

**B. Pythagorion Formation (Middle Miocene)**

(Py1) Thick-bedded and massive limestones. Lithofacies (a).

(Py2) Thin-Medium-bedded limestones with occasional marly intercalations. Lithofacies (b) and (d). One main horizon of Unit (Py2), 10-15m thick, is sandwiched between the thick bedded limestones of Unit (Py1). The total thickness of Pythagorion formation within the study area is ~80m.
Figure 7. Geological map and Longitudinal Section of the Eupalinos Aqueduct.
Tectonic formations

(Te) Tectonic breccia. It occurs along major faults and it has resulted in the tectonic reworking of the molassic formations along faults and major discontinuities. It consists of highly broken limestone into fragments of various dimensions from gravels to blocks, with ranging proportion of reddish brown clayey to sandy matrix. Very loose rockmass to cohesive tectonic rock, due to secondary cementation. Engineering geological information about the formation is presented in Table 1.

5 Geological structure along the aqueduct

5.1 Tectonic structures

The Pythagorion and Hora formations dip towards NNE with a mean dip/dip direction of 20°-025° (Fig. 8). Folding and faulting have developed during the dynamic tectonic regime of the final orogenetic stages and faulting during the Pliocene - present extensional regime (Ring et al., 2007, Boronkay & Doutsos, 1994, Chatzipetros et al., 2012). Although the mean dip of strata remains constant, these structures bend and deeply dissect the strata in mesoscopic and macroscopic scale, which is significant for the scale of the specific study.

From direct measurements of folding axes and by the deviation of strata measurements (Fig. 8), one main direction of folding was recognized, which is sub-parallel to the strata (WNW-ESE) and one secondary, almost perpendicular to the first (NNE-SSW).

The orientation of the discontinuities (faults and joints), regardless of their age and movement characteristics, is more or less similar to the fold axes (Fig. 9). NW-SE to E-W trending discontinuities dominate, whilst NNE-SSW are the main subordinates. Dip angles of 60-85° are prominent, but smoother angles are not uncommon. Most of the large discontinuities that were examined show very little or no displacement. The larger faults show offsets in the order of 0.5-5m and it is appreciated that the offset is very rarely larger than 10m. The exception is the Pythagorion fault that forms the boundary between the Kastro hill-range and the Hora plain, which is considered to be active (Chatzipetros et al., 2012) and according to Meissner (1995) its vertical offset is in the order of 200m. Likewise, the offset of a large fault located at ch. 400 of the tunnel is appreciated to be between 10-50m.

The faults show both normal and reverse character, sometimes depending on deviations of the dip direction along almost vertical faults. However detailed kinematic analysis was not necessary for the aims of the geological study. Larger faults usually accompany folds.

The mode of tectonism is in close relation with the type of the involved formations. The harder and more homogenous massive to medium-bedded limestones deform in a more rigid way, forming broader folds and zones of intense cataclasis. In cases, the fracturing of the limestones obviously coincides with bending of strata. The much weaker thin-bedded and fissile horizons show frequent
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Chevron or asymmetric folds, accompanied by smaller and close-spaced faults. Differential tectonic or sedimentary deformation occurs along the contact between fissile horizons and benches of limestone, frequently forming structures like small-scale folding, striations on the bedding planes, secondary cleavage and boudinage. These structures significantly degrade the geotechnical characteristics of these surfaces.

5.2 Geological structure of the aqueduct and its engineering geological significance

The description of the aqueduct starts from the south and proceeds towards the north, aiming to follow an order from the older to the younger geological formations. That means that the chainage (ch.) of the tunnel appears in descending order (see Fig. 7).

‘Urban segment’ & Tunnel’s south portal (ch. 1036 – ch. 1000)

The opening of the south portal of the tunnel was an interesting start for Eupalinos, from a geological point of view. The first 36m of the tunnel (ch. 1036-1000) are characterized primarily by the fault zone, composed of loose to well cemented tectonic breccia (ch. 1000-1030). Secondarily (ch. 1030-1036), the tunnel is covered by colluvial deposits, as well as man-made deposits produced during the excavation of the tunnel. Water is dripping in the tunnel especially during rains, percolating from the surface through the breccia. About 21m of archeaic and modern lining are constructed in this section (ch. 1015-1036), pointing out the stability problems during excavation and later. The unlined section of the tunnel is characterized by uneven morphology and cave-ins, whilst failures such as fall of gravels and blocks are possible (Fig. 10). Deformation and fracturing of a section of the archaic lining is also present (Fig. 11).

The boundary fault plain of the Pythagorion fault zone obliquely transects the tunnel at ch. ~1000, formed on massive limestones of Pythagorion formation. The fault plain dips with an angle of 45° to the SSW and it is covered by fault gauge (Fig. 10).

Section between two major faults (ch. 1000 – ch. 400)

Between the Pythagorion fault and another important fault zone at ch. ~400, all the higher part of Kastro hill is structured by strongly lithified / silicified massive or thick-bedded limestones, separated by stratified horizons of platy to medium-beded limestones with intercalations of marls. The massive limestones form strong benches on the hill’s surface, as well as some vertical slopes along large WNW-ESE discontinuities (Fig. 3 and 4).

These rocks compose both the Pythagorion and Hora formations and they are mapped as Units (Py1) and (Py2) for Pythagorion and (Ho5) and (Ho6) for Hora formation (Fig. 7).
The boundary between Pythagorion and Hora formations, as shown in Figure 2 by Meissner, is conventionally placed along the traceable contact between an overlying, 35m-thick, stratified horizon and an underlying massive limestone horizon.

Between ch. 1000-550 the beds gradually sink towards the north portal, undulating because of successive broad synclines and anticlines, 10-100m in width. Along this section the tunnel was constructed exclusively in Pythagorion Units (Py1) and (Py2). Massive to medium bedded limestones cover the larger part of the section, providing a stable and generally well formed cross section, although the rocks would have been hard to bore. Minor stability problems are encountered within these lithofacies, such as narrow cave-ins and possible fall of gravels and small blocks along major discontinuities and fractured zones.

Horizons of thin-bedded limestones with marl intercalations cover a smaller part in this section and they are related to one main location of failure, where platy rockmass has been detached from the roof (Fig. 12). Within these layers the impressive 'meeting point' has been formed at ch. ~610 (Fig. 5), where only minor problems exist. The north team of labourers formed the roof along a north-dipping bedding plane, in order to increase the height of the tunnel.

The thinly-bedded layers form impermeable horizons; the water in the overlying horizons moves along the contact and gathers into synclines. Limited seepage takes place when the tunnel cuts these horizons or cuts joints which are being fed with water by these layers. The main location of seepage is at ch. ~680 where an engraved water tank was constructed from stone during the byzantine era and massive calcite deposition has taken place (Fig. 13).

At about ch. 550 the boundary between the Pythagorion and Hora reaches the roof of the tunnel. However, it doesn't cut through the tunnel in this chainage mainly because between ch. 550-400 the tunnel drives subparallel to the general trend of the strata.

Along this segment, the north working team excavated the second branch of a triangular deviation and they faced the problem of having the strata dipping from the side towards the centre of the tunnel. The overlying stratified Hora unit (Ho5) closely follows the tunnel roof. In some sections, the Hora layers enter the tunnel and form its roof and its east wall, as they are being undulated and displaced by folds and faults. They are also related to minor water dripping in the tunnel, as they act in the same way as the above mentioned marly layers of Pythagorion. The rest of the cross section is structured by thick-bedded limestones of Pythagorion formation. These sections are commonly characterized by many small and medium scale instabilities, as well as one large failure which has formed a voluminous cave-in at ch.531 (Fig. 14). Detachment or sliding along clayey layers of the thin-bedded and occasionally mylonitized rockmass is present in the Hora layers. Some significant cave-ins occur within the massive limestones of Pythagorion, as they are characterized by fault zones and intensive fracturing in places (Fig. 15). Despite the problems for the north team in this section, the fact that limestone covers a large part of the cross section, helped them to proceed with only temporary support of the roof.

**Ch. 400 to the north portal - Coping with poor ground conditions**

A significant change in the formations occurs at the fault of ch. 400, which steeply dips to the NW. In the tunnel, about a 15m wide zone of tectonic breccia is formed along the fault, separating...
Pythagorion unit (Py1) to the south, from the Hora unit (Ho4) to the north. Cave-ins occur along this zone, as well as potential gravel and block falls (Fig. 16).

On the surface, the fault separates the strongly lithified / silicified limestone benches of unit (Ho6) from the shaly – thinly bedded alternations of unit (Ho3).

Between ch. 400-235 the tunnel is structured by unit (Ho4), which is composed by alternations between strong benches of massive limestones and weak horizons of clay shales and marls. The unit (Ho4) is considered to be a transitive unit between the calcareous and the clastic sedimentation of Hora formation. The absence of this unit from the surface possibly implies the control of the fault on sedimentation.

The bedding of this Unit in the tunnel dips almost perpendicularly to the tunnel axis towards the north portal, with angles between 25-40° or steeper. The groundwater follows the impermeable clayey and marly horizons providing minor dripping in the tunnel, as well as two locations of flowing water. A beautiful ‘room of stalactites’ forms at ch. ~280. Detachment or sliding on the roof of weak and tectonized fissile layers along clayey horizons occur in this section (Fig. 17), as well as detachment of some limestone blocks which are surrounded by clayey material or cave-ins along fractured zones in the limestone. Within this section the first branch of the triangular deviation was carried out by the north team. It is believed that the aim was to turn the axis perpendicular to the dip direction. This choice provides better stability of the cross section and quicker passage of the weak and water-bearing horizons.

Unit (Ho3) overlies Unit (Ho4) and outcrops on the surface northern than the fault at ch. 400. As the beds gradually sink towards the north portal, Unit (Ho3) is met at ch. 235 (where another fault is present) and covers the tunnel till the portal (ch. 235-0). Approximately 210m of archaic and roman lining was constructed in this section, testifying to the stability problems encountered during construction and later. Because of the presence of the lining, the geological structure was interpreted by the evaluation of the geophysical data, the mapping on the surface and by observations made within the ‘windows’ of the lining and on the floor of the tunnel. The weak clayey shales and marls and thinly-bedded limestones of Unit (Ho3) are characterized by frequent folding in mesoscopic and in broader scale, accompanied by faulting. The Unit enriches in thin-bedded limestone towards the north portal (ch. 80-0).

The presence of poor rock and discontinuity conditions, together with the presence of underground water, circulating along the surfaces between permeable and impermeable layers, led to poor stability of the tunnel cross section.

Detachment of platy and fissile blocks of rockmass from the roof, water inflow and rock sliding along slippery bedding dipping mainly from the west wall towards the center of the tunnel, characterize the excavation conditions within this section. It is possible that the instabilities which could affect only the roof were faced with temporary support measures.

Figure 14. Roof and wall instability in thin-bedded folded and faulted horizons.

Figure 15. Instabilities along fractured zone.

Figure 16. Longitudinal tunnel section across the fault zone at ch. 400.

Figure 17. Instabilities along the contact between massive limestones and weak fissile layers (around ch.310).
during the archaic excavation. The problems in those parts arose later by the gradual deterioration of the rockmass and they were faced by the Romans (Fig. 19). Eupalinos with his exemplary lining, which is still speaking to us by the word ‘ΠΑΡΑΔΕΓΜΑ’ written in red at ch. 180, secured the tunnel from the water bearing and slippery horizons.

The archaic lining locally suffers damages (Fig. 18), such as dislocation and fracturing of its roof members and cross section distortions, which are mainly attributed to overloading from the surrounding weak rockmass. The masonry blocks forming the lining are in large parts cemented together by calcite deposition.

**Spring segment of the aqueduct**

The spring segment of the aqueduct was constructed successively in Units (Ho3), (Ho2) and (Ho1) along its course to the spring. Approaching the top of the Hora sequence, platy limestones become more frequent. About 70m from the conjunction between the spring segment and the tunnel, a rockslide affects the hill slope, a few meters downslope of the axis of the aqueduct. The slope is steep at this location and it has formed along a stream and a fault. Blocks of platy limestones with marl intercalations slide along a weak layer of marl (Fig. 20). The rockslide has not damaged the aqueduct yet. No other significant engineering geological problems were detected along this part.

At the location of the spring, a cistern was excavated within platy limestones. Complementing the legend of the monument, a small old chapel is founded over the tank, which is now accessible through a narrow trapdoor. The rock walls of the cistern below the chapel are perfectly stabilized by calcite deposition (Fig. 21).

**6 Closing remarks**

The main engineering geological problems along the tunnel are related to the presence of marl and clayey shale horizons, and the intense fracturing of the limestone along major faults. Marls and shales provide to the molassic rockmass heterogeneity and low shear strength, as well as water movement along their contacts with overlying limestones. They are mostly present in the Hora Formation that dominates in the northern part of the tunnel. Transformation of massive limestone into tectonic breccia is most characteristic along the Pythagorian fault, at the southern portal, which is considered to be active. The orientation of bedding and discontinuities in relation to the tunnel direction, also affects tunnel stability. The reinforcing/strengthening action of the calcite deposition on the tunnel walls is apparent in many places.

Practically, Eupalinos has faced the most significant geotechnical challenges successfully, with the help of mathematics and geometry and with a sound understanding of the ground conditions.

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Figure 20. Rockslide area along the spring segment of the aqueduct.

Figure 21. Calcite deposition on cistern wall (at right).

References


