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NON-SEISMIC SURFACE FAULTING: THE PERAIA FAULT CASE STUDY (THESSALONIKI, N. GREECE)

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ABSTRACT

During the last months of 2005 a surface rupture started to form in Peraia suburb southwest of Thessaloniki city, located at the southern shore of Thermaikos bay in northern Greece. The rupture is concave, with one branch trending WSW – ENE, while the other one trends WNW – ESE. It dips towards the N and is located along the scarp that defines two morphological plateaus. These two plateaus are the top surfaces of the hangingwall and the footwall respectively of the well known, mapped and studied Anthemountas fault. This is a large active normal fault that bounds the southern margin of Anthemountas valley and controls the shoreline at its western extension. It is believed to be associated with certain large historical earthquakes, while its recent activity is documented by microseismicity. It is one of the most hazardous earthquake sources for the city of Thessaloniki. Four boreholes (G1-G4) have been drilled on both sides of the rupture, in order to examine the stratigraphical and geotechnical properties of the faulted geological substratum as well as possible water level fluctuations. Furthermore, correlation of boreholes G1 and G2 shows that there is a vertical displacement of at least 35 m during the Quaternary. Trenching along the fault has also proved that the surface rupture coincides with the main fault zone, showing a very large vertical displacement, non measurable in the trench. Periodic measurements of the water level in a number of boreholes used for irrigation have shown that there has been a significant fall of the water level during recent years. In conclusion, it seems that the Peraia rupture has been formed along the already existing Anthemountas fault and at least a part of the total displacement is attributed to overpumping.

Keywords: surface ruptures, active faults, creep

INTRODUCTION

During the 2005-2006 seasons, a set of surface ruptures has been observed at Upper Peraia urban area of Municipality of Thermaikos (suburb of Thessaloniki, Macedonia, northern Greece); the fractures are deforming both streets and buildings. These ruptures were studied using surface mapping, borehole data and stratigraphic correlation in order to define their origin, growth and slip rate. Ruptures appear at the lower part of the scarp between the hilly upper Peraia and the coastal lower Peraia plateaus. It is believed that the ruptures are caused by either the aseismic creep of Anthemountas Fault (Peraia segment) or the overpumping for water supply of Peraia town, but probably by both factors.

SURFACE RUPTURES

The surface ruptures extend at a length of *ca.* one kilometre in Peraia urban area close to the Thessaloniki – N. Michaniona road. They are traceable from Pissalides Clinic to the east, up to Kyprou Street at a WSW-ENE direction, whereas from Kyprou up to Mideias street (Lower Peraia) its direction changes to WNW-ESE (Fig. 1). The maximum vertical displacement of the ruptures has been measured at the Agnostou Stratioti and Megalou Alexandrou streets. Surface ruptures have also been

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observed on the Thessaloniki - Epanomi road, 3 km west of Peraia, as well as at Lower Peraia at the broader area of Philippou street.

According to descriptions of the locals, the surface ruptures were initially observed as small fissures during June 2005 at Agnostou Stratioti Street (Upper Peraia). Rupturing continued by lateral extension of the fracture line and in November 2005 it affected a three-storey building at Agnostou Stratioti Street, which was damaged so severely that it was declared unsuitable for living. Until March 2006 two more two-storey buildings at Kyprou and Mideias streets were declared fit for demolishion. Later on, serious damages have been observed in two more buildings in Upper Peraia and on street pavements (figure 1). The ruptures affecting the roads and the buildings are shown in photographs. The phenomenon is still evolving and new observations (January 2007) show that while the main rupture seems to have passed its peak phase, new fractures and building damages have been formed north of the main fault line.

Eirinis Street

Agnostou Stratioti Street

22-3-2006 28-8-2006

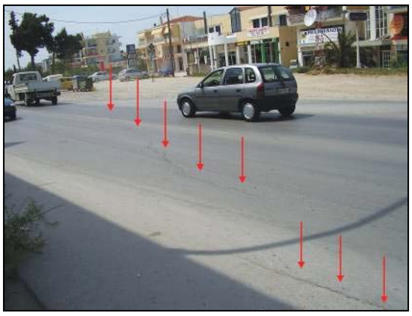
Agnostou Stratioti Street

Megalou Alexandrou Street



Kyprou Street

Mideias Street



Road Thessaloniki – N. Michaniona

Villas Victoria


Pissalidis Clinic

Road Thessaloniki - Epanomi

Figure 1. Photos showing various cases of surface rupturing in Peraia.

GEOLOGY – TECTONICS

The broader study area is located at the Axios geotectonic zone (Paionia subzone), consisting of Mesozoic rocks, outcropping as small hills in the area of Tagarades, Souroti and Sholari villages. All the remaining area (from Chortiatis mountain foothills up to west Chalkidiki and Thermaikos Gulf) is covered by mainly clastic (conglomerates, sands, clays) and locally calcareous (limestones, marls) sediments. According to Syrides, 1990, these sediments were deposited in successive complex depositional palaeoenvironments during Miocene (fluvial, continental red beds, brackish clays, sands, limestones), Pliocene (fluviolacustrine sands, silts, lacustrine marly limestones), and Pleistocene (continental red beds). The total thickness of these sediments is up to ~500m in the area of Peraia but exceeds ~2km in the centre of Thermaikos gulf. An intensive tectonic activity, during Upper Pleistocene, heavily affected the area and the Anthemountas graben was formed (Syrides, 1990). As a result a tectonic terrace (Upper Peraia plateau) was formed in the south margin of Anthemountas graben.

The Upper Peraia hilly plateau consists of alternating beds of grey-whitish to gray-greenish sands, gravels, sandstones, marls of Pliocene age (Gonia Formation, Syrides, 1990), and locally in the top brown-red clays with sand, gravels, cobbles, calcitic concretions of Quaternary age (Moudania Formation, Syrides, 1990). The Pliocene Sandstone - marl beds (Gonia Formation) is inclined about 5^0 to the South (N $180^o/5^o$). An important characteristic of the Pliocene sediments is that the sand - gravel beds contain significant amounts of pebbles from volcanic rocks (Syrides, 1990), and favoured a lot the stratigraphic study of the core samples. The fault trace separates these sediments from the recent fluvial and the sandy coastal deposits at Lower Peraia area (Fig.1)

The main faults in the broader area of Peraia are located south of it, striking E-W in the area of Plagiari and Trilofos villages, but the older ones strike N-S (IGMR, Epanomi sheet). These faults define the boundary of the Sandstone – Marl series and the Red Clays series, both of Pliocene age. The largest fault is the Anthemountas fault, which has a strike of E-W and a visible trace between Galarinos village to the E and Angelochori to the W (Neotectonic Map of Greece, Thessaloniki sheet). It defines the boundary of the Sandstone - Marl series and the recent coastal deposits at the area of Thermaikos Municipality, as well as the southern morphological boundary of Anthemountas basin at the broader area of Vasilika.

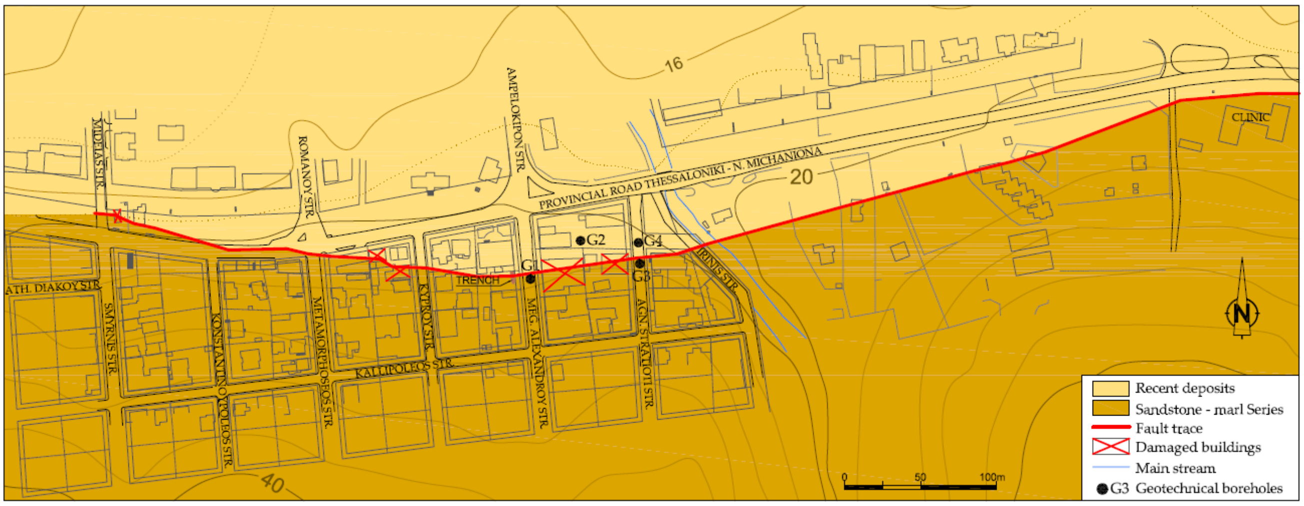


Figure 2. Map of Peraia urban area.

TECTONIC – SEISMOTECTONIC SETTING

The surface ruptures observed at Peraia are part of the longer active fault, known as the Anthemountas Fault (Neotectonic Map of Greece, Tranos et al 2003, Goldsworthy et al 2002). The fault extends from the coastal area of Megalo Emvolo Cape, north of Angelochori village, with an E-W strike up to Galarinos village, with a total length of 32 km. It is a normal fault dipping to the north and divided into three segments (Fig. 3) based on the geometrical characteristics of the surface fault trace and the hypothetical extension to the sea area of Thermaikos Gulf. The first segment (1) extends from Galarinos to N. Risio with direction $N110^0$ and length 17 km. The second (2) segment extends from N. Risio village to Megalo Embolo Cape (Angelochori) with direction $N90^0$ and length 15 km. The third (3) part is the hypothetical extension of the fault into the sea with direction $N90^0$. The dip direction of the fault is 87^0 to the North near the surface, but deeper than 8km the dip decrease to 50^0 at 20km depth; it is therefore a listric fault.

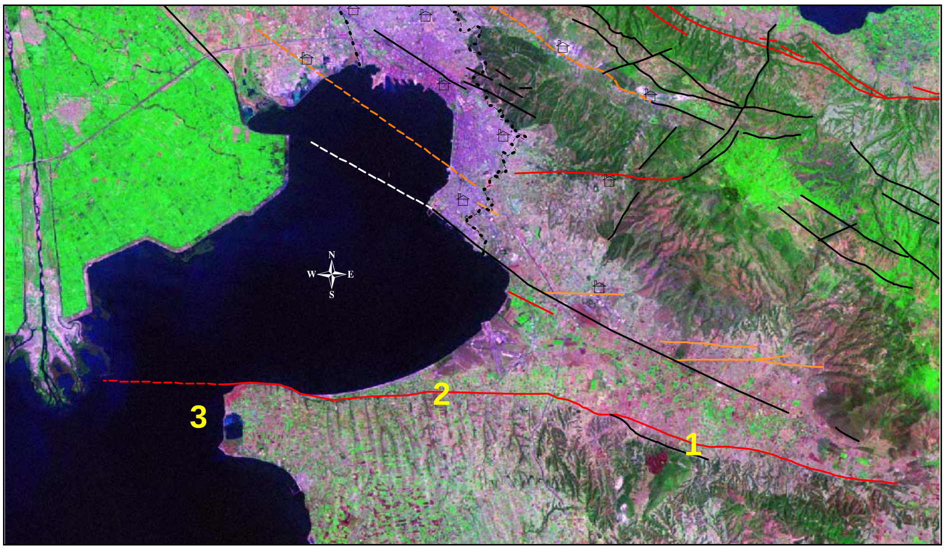


Figure 3. Landsat 7 Image (2000) shows the Anthemountas fault with red color and its segments.

The Anthemountas fault is best visible in satellite images due to its intense morphological expression. The fault trace represents the boundary between Neogene and Quaternary deposits (Figure 2). It is characterized as an active fault due to the vertical relationship of its orientation (E-W) to the present stress field (N-S). It affects Pliocene and Quaternary deposits, forming an intense morphology with tectonic terraces and asymmetric development of the Anthemountas river network. The fault is connected with a seismic series of microseismicity during 1988, but also with moderate to large historical earthquakes (Vasilica 1677, M=6.2 and possibly with the catastrophic earthquake of Thessaloniki area at 1759).

GEOMORPHOLOGY

The wider hydrological basin of Municipality of Thermaikos consists of several small parallel torrent valleys, of low (1st to 4th) order, according to Strahler's classification. Torrent valleys develop with a parallel longitudinal direction from South to North and reveal an open V to U shaped morphology with steep slopes (figure 4). To the North these valleys were cut off by the W-E trending Antemountas fault. As a result a tectonic terrace was formed (Upper Peraia plateau) and the loose debris (from the torrents and colluvial deposits of the fault) gradually filled the low coastal area of Thermaikos Golf (Lower Peraia plateau).

Presently, the slope dips vary between 10^0 to more than 55^0, developing in some cases steep scarps of up to 15m high (I.G.M.R. Geotechnical Engineering Geological map). Three hydrological basins aexist at the Upper Peraia area, with two streams of 2nd order and one of 3rd order; only one of them though is channeling to the Lower Peraia and discharge into the Thermaikos bay.

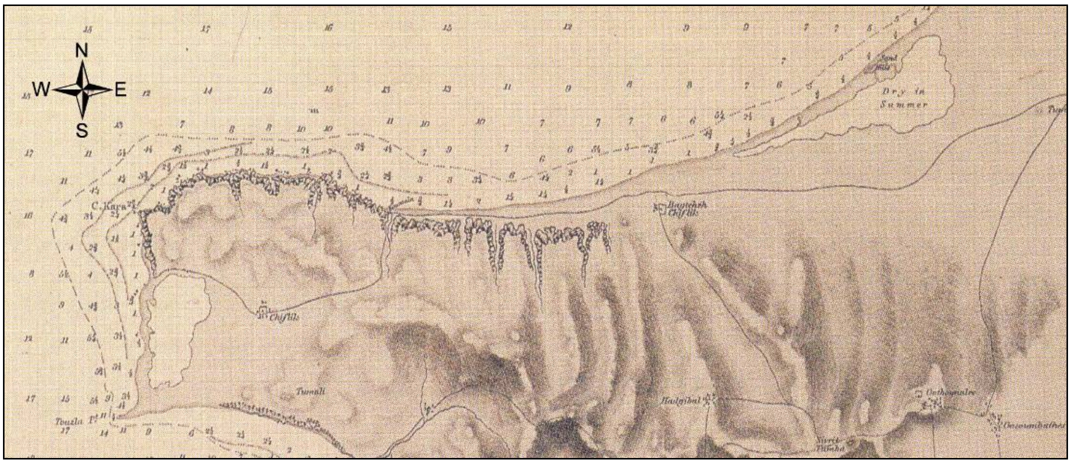


Figure 4. Morphological map of Thermaikos area (British Admiralty London, 1851, from Demertzis, 1999).

Because of the recent build up of the area, the slopes have been strongly affected and smoothed with artificial banking up. In the few cases where the natural slopes are observable, their height reaches 5 m. Several morphotectonic indices, such as knickpoints of streams and mountain-front sinuosity have also been calculated, and they support the recent activity of the fault.

Knickpoints or steps are formed along valleys after cut off by a normal fault (Burbank & Anderson 2001) and appear as steps in a longitudinal profile of the valley. Below the knikpoint the erosion rejuvenates, causing the uphill migration of the step. Rock types, even human influence, can effect this migration. Knickpoints, connected with the Anthemountas fault trace, were observed into four successive torrents in urban area of Peraia, at altitudes of 12 to 18m.

The Mountain – Front Sinuosity index (Bull 1977, 1978) expresses the equilibrium between the erosion forces and the tectonic forces. Its formula is S=L/l, where L is the length of a specific isoline and l is the length of a straight line at foothills. When the foothills have been developed from recent activity of the faults they are rather straight and have low values of S (1.0-1.6). For the Anthemountas fault and the Peraia segment (from N. Risio to Angelochori) the rates are very low and vary from 1.03 to 1.64, indicating recent tectonic activity.

GEOTECHNICAL BOREHOLES

In order to study the geotechnical conditions of the material deformed by the surface ruptures, four (4) geotechnical boreholes (G1, G2, G3, G4), with core sampling, were drilled during June 2006, on both sides of the surface ruptures at Agnostou Stratioti Street (G3, G4) and Megalou Alexandrou Street (G1, G2) at Upper Peraia build area (Fig. 2). Two boreholes were drilled at the footwall of the fault trace (G1 with depth of 15.45 m and G3 at 15 m) and two boreholes at the hangingwall (G2 at 54m and G4 at 28m).

Logging of these revealed the stratigraphical and geotechnical properties of the deformed materials at both sides of the surface ruptures. In the boreholes drilled at the footwall, the Pliocene basement of the area (Sandstone – marl series) was found at 2 m depth, exactly under the recent backfills. These series consist of alternating beds of clays, marls, sandstones, sands and gravels, light brown to brown-greenish in colour. The formation is characterized by the penetration tests (SPT) as dense to very dense with N=25-50. At the hangingwall and below the backfills, Quaternary deposits (clays, sands, gravels to pebbles, brown to brown-red colour) were drilled up to 14m (G4) and 30m (G2) depth. This formation was deposited after the activation of the fault (eroded material from the hanging wall) and is characterized with the penetration tests (SPT) as medium dense with N=10-15. Below the base of Quaternary deposits, the Pliocene basement of the area (Sandstone – marl series) was found, in G4 at 14m depth and in G2 at 30m depth. This difference is due to the large inclination of the fault at 86^0 to the North.

Measurements of water level in these geotechnical boreholes (Table 1) indicate a 7 meters drop of water level between the two sides of the fault.

Table 1. Ground water Levels

DATE	8/6/2006	24/8/2006
G1	5,82	6,23
G2	12,00	-
G3	7,00	7,25
G4	16,68	17,30

HYDRO-BOREHOLES

Water supply for the urban area of Peraia comes from six boreholes (H1-H6) after pumping (Figure 4). Two of these boreholes are at the hangingwall of the surface ruptures and close to them (H1 & H2), while H4 is located at the footwall upper of the ruptures is the H4 (Fig.5). The hydro-borehole H2 is near the coastal line, while the H5 and H6 ones are at the footwall, at both sides of Peraia. The boreholes G1, G3 and G4 which are located close to the fault trace are pumping almost 145m^3/h. Due of the continuous operation of the boreholes, it was impossible to measure the piezometric ground water levels at rest condition and compare them with previously measured water levels. The only measurements they are comparable are those of the H3 borehole (Table 2).

Table 2. Piezometric water levels at H3 hydro-borehole

DATE	WATER LEVEL (m)	CONDITION
13-9-1998	25,00	Construction
27-4-2005	36,30	-
6-5-2006	44,45	Pumping
30-8-2006	36,50	1 month rest
12-10-2006	43,00	48 hours rest

Generally we have observed a fall of piezometric ground water level which is very difficult to quantify. The Municipality of Peraia has drilled two new boreholes, for the replacement of the H1 and H3. The H1 and H3 will be used for the monitoring of the ground water level.

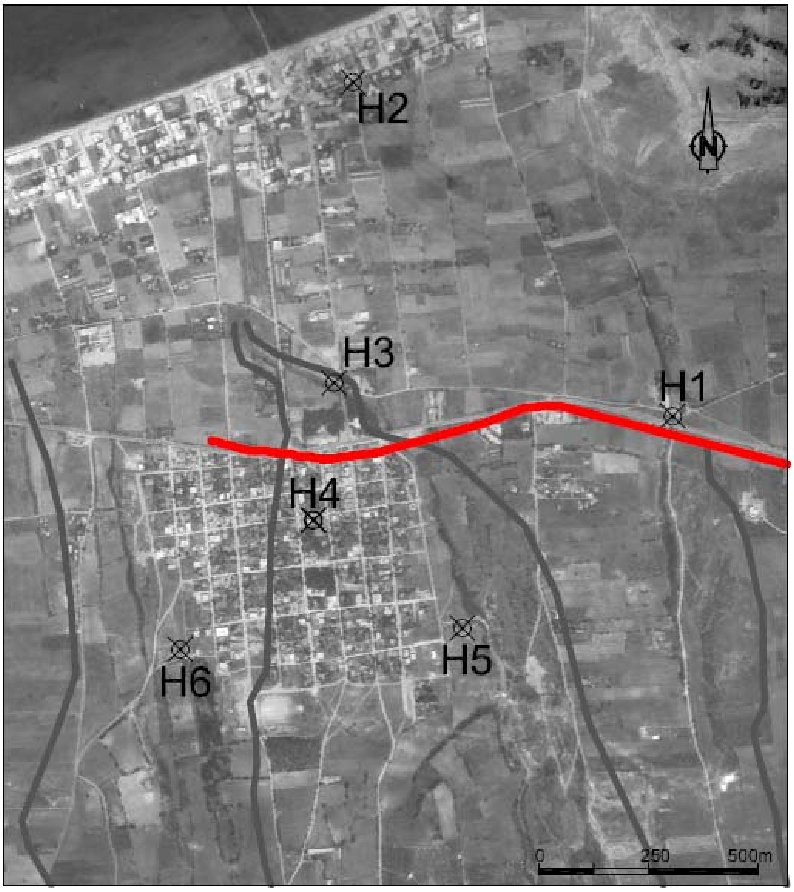


Figure 5. Aerial photo (21-6-1979, H.A.G.S. 3000.M) of urban area of Peraia with the Hydro-boreholes (H1-H6), the Hydrological basins and the fault trace

DISPLACEMENT MEASUREMENTS

In order to monitor the displacement at the fault trace, a topographical survey has started and is under way for defining the horizontal and vertical displacements. The measuring points were installed at pavements and walls of the buildings. The opening between the measuring points were periodically measured with a caliper (accuracy 0.1mm), to define the horizontal, vertical and strike slip displacements. The measurement results until now show a displacement of 25-50mm per month.

An inclinometer (SINCO 50310900) has been installed in borehole G2 for measuring the rate of horizontal displacement. The first inclinometer showed a small displacement and was damaged after 2.5 months at the depth of 27.5m. The damage is attributed to the continuous slip of the fault at this depth, which is the contact between Sandstone – marl series and Quaternary deposits. A second inclinometer was installed 0.70m north of the first. The records show a displacement to the north at the depth of 37m (fault surface) with a rate of 0.5mm per week.

TRENCHING

For further investigating the faulting, a trench was excavated perpendicular to the fault trace, at Megalou Alexandrou Street. The depth of the trench was 2 m. Both walls of the trench were logged in a 1:20 scale, using an auxiliary 1 x 1 m grid. The microstratigraphical and structural analysis of the loggings showed that there is no connection between the footwall and the hangingwall, as the continuation of the layers was abruptly disrupted at the fault trace. The hangingwall consisted almost exclusively of footwall colluvial deposits, meaning that the fault displaced the sediments by more than 2 m visible in the trench (as a matter of fact, the actual displacement has been defined by borehole data at about 35 m). This is evidence that the surface ruptures are not just an occasional phenomenon, but are directly associated to the tectonic activity of the Anthemountas fault.

CONCLUSIONS

In this paper the active fault of Anthemountas, which is located at the urban area of Peraia, was studied. Aseismic movement activity was observed along this part of the fault since June 2005, with surface ruptures over the fault trace for a length of 1km. As a result of the rupturing, four buildings are due for demolition, while two more suffered serious damages. Lighter damages are recorded to other buildings and the local street network. For further studying this phenomenon, four boreholes were drilled for investigating the stratigraphical and geotechnical properties of the deposits near the ruptures. In one of them an inclinometer was installed for measuring the horizontal movements. The water level changes were also measured, despite their reliability being rather low, and an exploratory trench was studied for defining the stratigraphic and structural relationships between the footwall and hangingwall.

From the combination of the various results it is estimated that the surface ruptures were caused because of the aseismic creep of a part of Anthemountas fault, trending E-W and dip towards to the N, which shows a vertical displacement of at least 35 m at this site. The measured rate of the horizontal movement is about 0.5mm per week and the rate of the vertical movement about 0.5cm per month during its peak period. The reactivation of the fault perhaps is partly due to overpumping of the aquifer for water supply, but one should take into account that this phenomenon has been observed many times during the Quaternary (as derived by trench logging and borehole correlation) and the water level variations are a circumstantial factor.

AKNOWLEDGEMENTS

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APPENDIX

SECTION OF GEOTECHNICAL BOREHOLES

M. THERMAIKOS - PERAIA — BOREHOLE SECTION G1 (M. Alexandrou - City Hall)

Elevation: 22m - Coordinates: x=408979 y=4483606 (EGSA'87)

DEPTH	(SPT) N	SECTION	STRATA DESCRIPTION
0			0,00-1,00: BACKFILLS
1			1,00-15,45: BASEMENT. Sandstone - marl Series. Alternation of clays, sands and gravels to sandstones in layers and lenticulars. Color light brown to brown - greenish. Calcerous concretions.
2			
3	24		
4			
5	46		
6			
7			
8			
9	23		
10			
11			
12	>50		
13			
14			
15	44		

M. THERMAIKOS - PERAIA — BOREHOLE SECTION G3 (Agn. Stratioti - Upper)

Elevation: 22,90m - Coordinates: x=409043 y=4483623 (EGSA'87)

DEPTH	(SPT) N	SECTION	STRATA DESCRIPTION
0			0,00-2,00: BACKFILLS
1			
2			2,00-15,00: BASEMENT. Sandstone - marl Series. Alternation of clays, sands and gravels to sandstones in layers and lenticulars. Color light brown to brown - greenish. Calcerous concretions.
3	18		
4			
5			
6	38		
7			
8			
9			
10	22		
11			
12			
13	>50		
14			
15			

M. THERMAIKOS - PERAIA — BOREHOLE SECTION G2 (M. Alexandrou - Lower)

Elevation: 19,90m - Coordinates: x=409006 y=4483639 (EGSA'87)

DEPTH	(SPT) N	SECTION	STRATA DESCRIPTION
0			0,00-1,50: BACKFILLS
1			
2			1,50-30,00: QUATERNARY FORMATION. Brown clay with sand and gravels occasionaly. Oxidazed.
3	13		
4			
5			
6			
7	27		
8			
9			
10	21		
11			
12			
13			
14	13		
15			
16			
17	11		
18			
19			
20			
21			
22			
23	23		
24			
25			
26			
27			
28			
29			
30			30,00-54,00: BASEMENT. Sandstone - marl Series. Alternation of clays, sands and gravels to sandstones in layers and lenticulars. Color light brown to brown - greenish. Calcerous concretions.
31			
32			
33			
34			
35			
36			
37			
38	>50		
39			
40			
41			
42			
43			
44			
45			
46			
47			
48	23		
49			
50			
51	75		
52			
53			
54			

M. THERMAIKOS - PERAIA — BOREHOLE SECTION G4 (Agn. Stratioti - Lower)

Elevation: 20,90m - Coordinates: x=409042 y=4483634 (EGSA'87)

DEPTH	(SPT) N	SECTION	STRATA DESCRIPTION
0			0,00-0,70: BACKFILLS
1			0,70-1,50: CLAY light green with fine sand and gravels.
2			1,50-14,20: QUATERNARY FORMATION. Brown clay with sand and gravels occasionaly. Oxidazed.
3	11		
4			
5			
6			
7	16		
8			
9			
10	16		
11			
12			
13	13		
14			
15			14,20-28,00: BASEMENT. Sandstone - marl Series. Alternation of clays, sands and gravels to sandstones in layers and lenticulars. Color light brown to brown - greenish. Calcerous concretions.
16	56		
17			
18			
19			
20	28		
21			
22			
23	27		
24			
25			
26			
27			
28			

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