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THE 3D GEOLOGICAL STRUCTURE OF THE MYGDONIAN SEDIMENTARY BASIN (GREECE)

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ABSTRACT

The geometry and dynamic properties of the main soil materials of a complex geological structure have a large importance for performing empirical and theoretical site effect analyses. In this paper the case of the definition of the geological structure of the Mygdonian sedimentary basin is presented. Located at about 30 km E-NE of the city of Thessaloniki (Northern Greece), it is the closest active seismic zone affecting it. The construction of the 3D model is based on array microtremor measurements as well as geological, geophysical and geotechnical data from the area derived during previous and recent surveys. The structure derived from the synthesis of all data includes a description of the geometry of the main soil formations within the basin and their shear wave velocities down to the bedrock. This structure was correlated with the basin response in terms of resonant frequency, as derived from microtremor, and from weak and strong motion earthquake recordings.

Keywords: 2D and 3D geological structure, microtremors, shear wave velocity, site response and resonant frequency.

INTRODUCTION

The importance of site effects and their study have been the main reason for setting up worldwide test-sites. Such sites allow a detailed analysis of seismic response observations based on the independent determination of the subsoil structure and properties. The scientific community has learnt a lot of knowledge in Seismology and Earthquake Engineering from the longest running test-sites such as Turkey Flat (U.S.A.), Ashigara Valley (Japan) and Euroseistest (N. Greece). In this paper the recent developments at the Euroseistest site (http://euroseis.civil.auth.gr) are presented. This site has been in operation since 1993. It is located in the Mygdonian sedimentary basin and has so far benefited from three European Research Projects: EuroseisTest (EV5V-CT.93-0281, 1993-1995), EuroseisMod (ENV4-CT.96-0255, 1996-1999) and EuroseisRisk (EVG1-CT-2001-00040, 2002-2005).

Euroseistest was originally conceived to contribute to the understanding of 2D geological structures on site response. With this aim, an extensive program of geophysical and geotechnical surveys across a selected 2D cross-section in an alluvial valley were deployed in order to determine the subsoil structure of the basin (Raptakis et al., 1998; Jongmans et al., 1998; Pitilakis et al., 1999; Raptakis et

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al., 2000). Based on the well constrained structure determined for that 2D North–South cross-section (Raptakis et al., 2000) different analysis have been made. Theoretical 2D response analyses (among them Chávez-García et al., 2000; Makra, 2002; Makra et al., 2001, 2005), for example have shown the large impact that surface geology has on ground motion. Those studies showed the importance of the waves diffracted by lateral heterogeneities such as the edges of the basin or lateral contrasts brought about by faulting within the sediments. Mygdonian valley, however is a 3D structure, and the selection of a 2D cross-section was a compromise between the need to study a complex valley and available resources. The continued use of Euroseistest has recently allowed tackling the determination of the geometry and properties of the subsoil within a large part of this 3D structure. To this end, an extensive program of passive (array microtremor measurements) and geophysical (seismic refraction) surveys was conducted. In this paper the main results of this investigation are presented together with the synthesis that shows our current understanding of the 3D structure for the Mygdonian basin.

GEOLOGIC AND TECTONIC SETTING OF THE MYGDONIAN BASIN

Mygdonian basin is located about 30 km E-NE of the city of Thessaloniki (Figure 1). The central and eastern parts of the basin belong to the Serbomacedonian massif, one of the most seismotectonically active zones in Europe, while its western part belongs to the Circum Rodope zone. Its basement consists mainly of gneiss, amphibolites, two-mica schist and marble intrusions. The sediments that fill the basin can be classified into two main units. The lower unit, namely the Promygdonian system was deposited during the Neogene in the Promygdonian basin (underlying the weathered basement). The upper unit, namely the Mygdonian system was deposited during the Quaternary within the younger grabens of the Promygdonian basin (Figure 2). The Promygdonian system consists of conglomerates, sandstones, silt-sand sediments and red-beds, while the Mygdonian comprises fluviolacustrine, deltaic, lacustrine, lagoonal and estuarine deposits (Psilovikos, 1977; Sotiriadis et al., 1983). The deeper system (Promygdonian) is thicker than the shallower system (Mygdonian). The two together form a sedimentary that varies along the central axis of the basin from 140 m close to Volvi lake (Raptakis et al., 2005), to 200 m, at TST site (Raptakis et al., 2000). It then increases thickness towards the West, and attains 400 m at the edge of the studied zone (BRGM, 1971). In the present study approximately 60 km^2 of the central part of the basin are investigated, between the Lakes Lagada and Volvi (rectangular box in Figure 1).

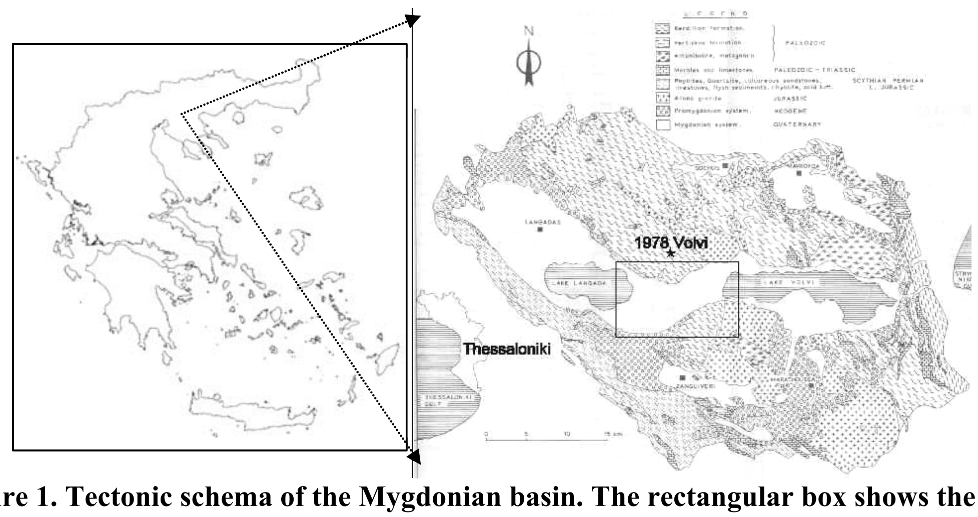

Figure 1. Tectonic schema of the Mygdonian basin. The rectangular box shows the area investigated in the present study. The star depicts the epicenter of the 1978 Volvi earthquake.

The graben is subjected to the two major tectonic phenomena observed in Northern Greece: the N-S extension of the Aegean Sea and the western end of the north Anatolian strike-slip fault (Papazachos et al., 1979). The main fault trends in the area are oriented NW-SE. Different directions of faulting, E-W and N-S, dominate the eastern part of the basin. The almost E-W trending 12 km long Vasiloudi - Gerakarou - Nikomidino - Stivos rupture fault system and its two segments is the main feature that runs through the southern and western parts of the Mygdonia graben (represented as F-GNSP for the main fault system and F-VL & F-Sx for its two segments in Figure 2). This fault zone exhibits a constant dip to the N with a dip angle of 70^0-80^0 which is reduced to about 35^0 as the depth increases. The escarpment of the F-GNSP fault was about 250 m during the Quaternary, while the slip rate during the Holocene–Pleistocene was 0.06-0.7 mm/year (Chatzipetros, 1988). This fault produced the 1978 Volvi earthquake M=6.5R (Papazachos et al., 1979; Mountrakis et al., 1983) which cost 45 human lives and damages to 25% of the buildings in the city of Thessaloniki.

Major earthquakes have occurred in the broader area of the Mygdonian basin, among which that of Assiros M=6.5R in 1902, Kresna M=7.1R in 1904, Ierissos M=6.0R in 1932, Sohos M=6.2R in 1933. The seismicity of the Mygdonian basin and its broader area is monitored by the permanent accelerometric array which operates since 1993. Today it consists of 18 high resolution 3D component surface and down-hole accelerometers installed in a cross-shape at the central part of the basin (Figure 2). 2/3 of the accelerometers are installed at the surface and the rest within boreholes at different depths (at sites PRO and TST). Most of the instruments are placed on alluvial deposits and four on rock outcrops or rock at depth (surface and down-hole stations at site PRO & STI and a down-hole accelerometer at TST). The array records the local and regional seismicity of the area on a continuous basis. The recordings are transferred via wire and radio transmission to Thessaloniki and archived in a central system, creating a high quality dataset of earthquakes accessible via the Euroseistest web-site.

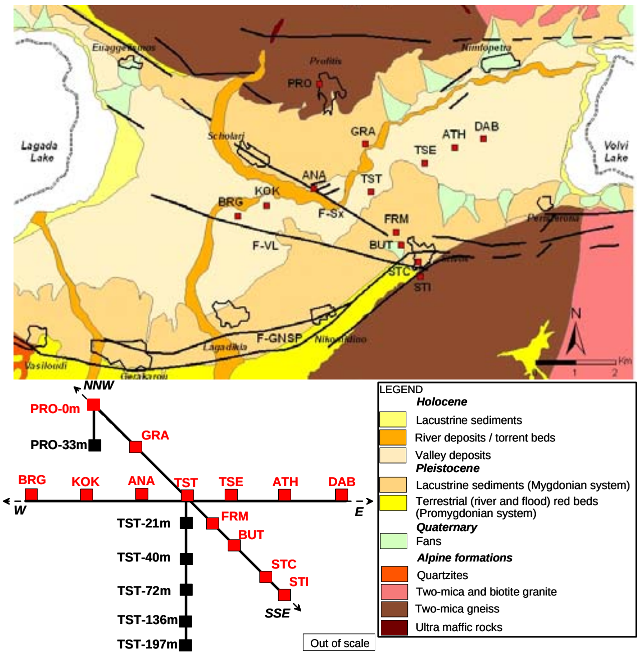

Figure 2. Top: neotectonic map of the Mygdonian basin (Mountrakis et al., 1997). Red squares show the strong motion array at the free surface, solid lines indicate faults. The outline of the villages bordering the basin is indicated with solid lines. Bottom: schema of the strong motion array. Surface instruments are shown in red, while borehole accelerometers are shown as black squares.

DATA USED TO CONSTRAIN THE 3D STRUCTURE

Previous knowledge of the Mygdonian geometry

The preliminary 3D model of the Mygdonian basin was constructed by BRGM (Bureau de Recherché Geologiques et Minieres) during 1971 (BRGM, 1971). This study, due to its objective (determination of the exploitation possibilities for the aquifer) concentrated on the bedrock interface using P-wave refraction surveys, electrical soundings and drillings (Figure 3). The synthesis of these data provided a 3D model which described only the geometry of the interface between sediments – bedrock and not of the intermediate layers. Media were characterized using V_p and not V_s velocities, which are necessary input parameters for site response analysis. According to this model the bedrock between Lagada and

Volvi Lakes forms a syncline with its axis parallel to East–West direction. The deeper part of this syncline lies at a depth of 400 m in the western part of the basin (see the contour labeled -300 in Figure 3, where depth is measured with respect to the mean sea level instead of relative to the free surface). The thickness of the sediments decreases to the central part of the basin where it is about 200 m (-100 to -120 m in Figure 3, after subtracting elevation), and maintains this maximum thickness towards the east. In contrast to the geometry determined by BRGM, the extensive program of geophysical and geotechnical surveys performed between Profitis – Stivos villages (N-S direction) in the framework of the Euroseistest and Euroseismod projects (1993-1999) showed thicker soil layers at the central part of the basin (about 150 m after subtracting elevation at TST site) and a shape that is different from the syncline-shape geometry (Figure 3). More recently, other 3D geometries for the basin were proposed. Most of them were based on electrical prospecting results (Thanasoulas, 1983; IGME, 2001; Tournas, 2005) and reproduced the BRGM model with only minor differences, other based on the resonant frequency map produced by site response analysis (see Figure 7 below) assuming the V_s velocity of the sediments to be constant throughout the valley (Manakou et al., 2004). None of the above studies succeeded defining a 3D geometry useful for site response analysis. This necessitated new geophysical and geotechnical surveys which were conducted within the framework of the European project Euroseisrisk (2002-2005). These surveys included seismic refraction, electrical surveys, array microtremor measurements, geotechnical boreholes, laboratory and in-situ tests such as Standard and Cone Penetration Tests (SPT and CPT respectively). In the following paragraphs the basic information on these measurements is given.

(a)

(b)

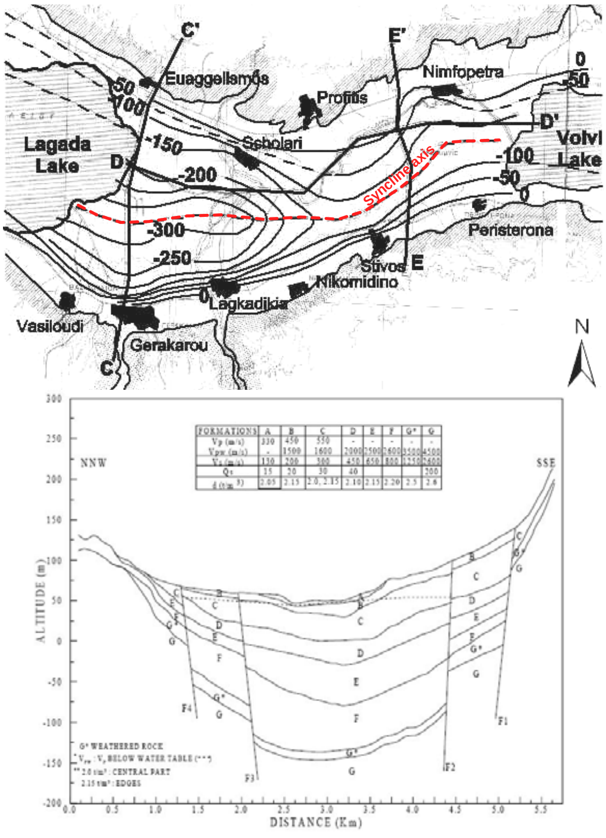

Figure 3. (a): Contours (in m) of the geometry determined by BRGM for the interface sediments - bedrock. Depth values are referred to the mean sea level. Lines EE´, CC´ and DD´ represent refraction profiles. (b) Detailed 2D model determined for the Profitis-Stivos section by Raptakis et al. (2000).

Seismic refraction survey

Two large-scale refraction experiments were carried out in 2003 and 2004 along an East-West direction in the valley (Figure 4). The aim of these experiments was to define the geological structure in terms of V_p and V_s velocities in the region between Lagada and Volvi Lakes. Two reverse linear profiles were conducted, covering a total distance of 8 km. Excitation was provided by 175kgr of explosives, fired inside boreholes of 30 m depth each at the edges of the profiles (SP1 & SP2 for 2003, SP3 & SP4 for 2004 experiment). 67 instruments (seismometers and accelerometers) were temporarily deployed in addition to the permanent strong motion array in the E-W direction. In addition to this, three shorter arrays of 24-ch geophones were disposed in the vicinity of the two profile edges. From the processing of the recordings (exp-2003 & exp-2004: explosion of 2003 & 2004 experiments respectively, geo-2003 & geo-2004: geophones of 2003 & 2004 experiments respectively in Figure 4), the P- and S-wave velocities of the main geological formations across the E-W direction of the basin were determined.

Electrical survey

Electrical tomographies and soundings were performed at the N and S-SE margins of the basin. These measurements were carried out to add detail to the geometry of the valley's edge. These zones of strong lateral heterogeneity affect significantly site response as they are the likely source of diffracted waves (Figure 4). For the tomographies, the 2D pseudosection was used (RES2DINV method, introduced by Loke and Barker, 1996), while for the soundings the standard AB/2 Schlumberger method was implemented. Although electrical methods cannot determine the mechanical properties of the geological formations, the resistivity mapping can give a rough estimation of the bedrock depth. The results of the electrical processing corroborated the borehole information from the vicinity. Their results clarify the dip of the bedrock at the valley edges (Final Euroseisrisk Report, 2005).

Array microtremor measurements

The Microtremor Exploration Method (MEM) is an alternative passive survey used to estimate the sub-surface layered earth structure (V_s vs. depth) by recording the vertical component of ambient noise. Its basic assumption is that microtremors consist predominantly of the fundamental mode of Rayleigh waves (Aki, 1957; Nogoshi & Iragashi, 1971; Okada, 1997; 1990). The measurement of the noise correlation between different stations, averaged azimuthally, allows determining the dispersion curve of the phase velocity. The phase velocity dispersion curve may be inverted to recover the shear wave velocity profile at the site under investigation (Asten & Henstridge, 1984). Ambient noise was recorded in 2005-2006 at 29 sites distributed within Lagada and Volvi region, covering its main geological formations (Figure 4). Noise was recorded continuously for 30 to 35 min in four broad-band seismometers Guralp (CMG-40T of 30 sec natural frequency), connected to four Reftek recording systems (DAS-130) and GPS units. At each site, three concentric circular arrays of different radii were deployed to investigate the layers at various depths. The data were processed using the Spatial Autocorrelation Coefficient method (SPAC) and the dispersion curve of the fundamental mode of Rayleigh waves was derived for 27 out of the 29 sites. Through use of an inversion code (Herrmann, 1987b) the S-wave velocity profile was derived down to the surface with the largest acoustic impedance (V_s, density), which for most sites coincides with the bedrock interface. At the sites where this was not possible, the combination of SPAC and HVSR method (Horizontal to Vertical Spectral Ratio, Nakamura, 1989) yielding an estimation of the bedrock depth. The soil profiles derived using this procedure was used as the main information for construction of the 3D model.

Geotechnical surveys

The geotechnical surveys included three sampling boreholes (ANA, TST, ATH) with SPT tests performed every 2m depth. Intact and disturbed samples were extracted for laboratory tests (Classification, Oidemeter, Triaxial tests). Additionally, 20 CPT measurements at sites close to the strong motion array stations were carried out (Figure 4). The parameters estimated by the CPT measurements were the cone resistance and friction ratio, which were corrected and used for the interpretation and classification of the soil samples. These results allowed to clarify the soil deposits using the USGS scheme down to 40 m depth (Final Euroseisrisk Report, 2005).

SYNTHESIS OF THE GEOLOGICAL STRUCTURE

The determination of the basin geological formations was based on the V_s profiles derived from the microtremor measurements and refraction surveys. The soil classification was based on Raptakis et al. (2000) proposal for the 2D Profitis-Stivos cross-section [where (A, B, C, D): Mygdonian system, (E, F): Promygdonian system, G*: weathered bedrock, G: bedrock]. V_s values were compared with previous geophysical surveys (Raptakis et al., 2000; 2nd Euroseisrisk Report, 2003). They were also correlated to each other along several 2D sections, in order to check their continuity throughout the valley. 17 2D cross-sections of different lengths and directions (11΄, 22΄, 33΄, 44΄, 55΄, 66΄, 77΄, AA΄, BB΄, CC΄, DD΄, EE΄, FF΄, KK΄, II΄, JJ΄, ZZ΄) were drawn (Figure 4). These 2D sections provide the stratigraphy of the central part of the Mygdonian basin, namely the geometry of the two main sediment systems (Mygdonian and Promygdonian), their V_s velocity range and the main tectonic features affecting them. The V_s velocity of the upper (A+B soil layers) and lower (C+D soil layers) Mygdonian system ranges between 130 to 275 m/sec and 275 to 450 m/sec respectively, while of the Promygdonian system (E+F soil layers) ranges between 450 to 1000 m/sec. Velocities greater than 1000 m/sec indicate the upper crystalline bedrock of the area. The 17 2D cross-sections were enriched by the geological information derived from hydrological and sampling boreholes (IGME, 2001; 2nd Euroseisrisk Report, 2003) and Cone Penetration Tests at the uppermost surface layers. Figure 5 depicts a typical 2D cross-section of roughly WSW–ENE direction. The data from the 2D cross-sections were interpolated at 200 m intervals in order to condense the information. The database thus created was the basic information imported into the Geographical Information System (GIS, ESRI, 1995) to create 3D models of the basin formations.

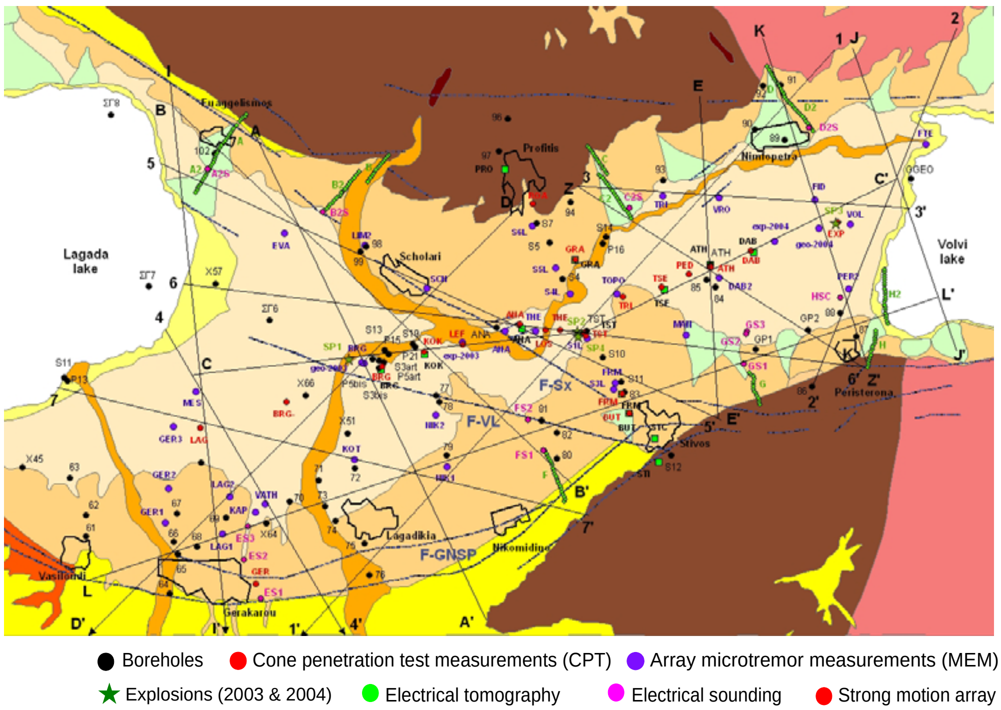

Figure 4. Data used for the 3D structure of the basin. The solid lines show the 17 2D cross – sections. The legend for the geological formations is the same as in Figure 1. The location of the different measurements are indicated: black circles indicate boreholes; red circles indicate cone penetration test measurements (CPT); solid mauve circles indicate array microtremor measurements (MEM); stars show the location of the shot points where explosions were fired during 2003 & 2004 experiments; small green circles marked with capital letters show the location of the electrical profiles; pink circles show the location of the electrical sounding; green squares indicate strong motion array.

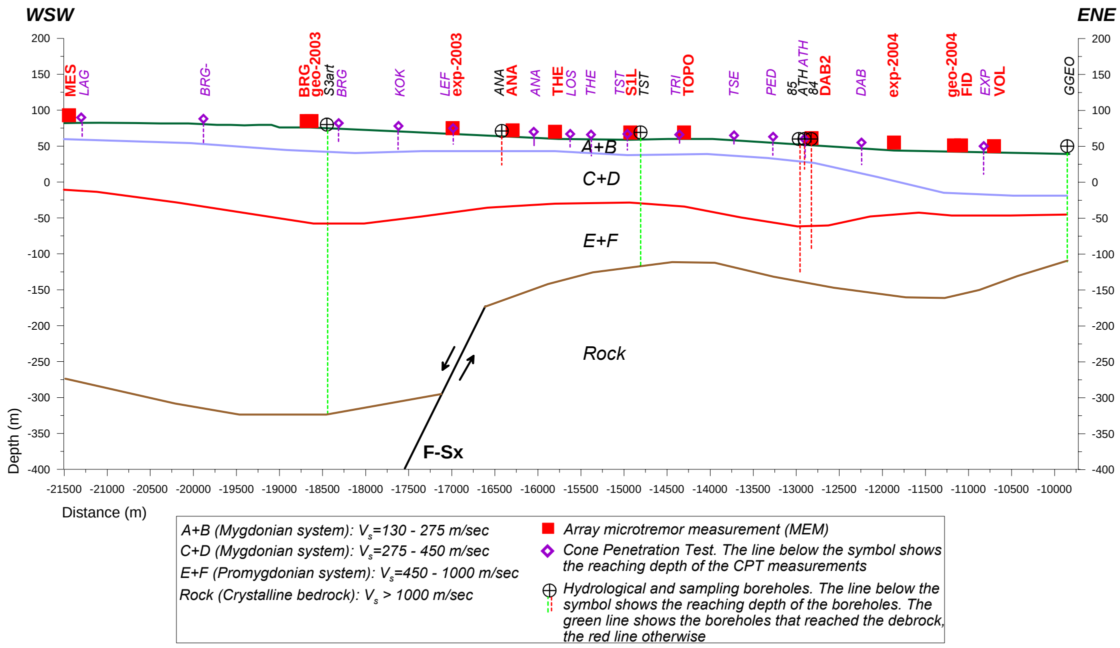

Figure 5. Geometry determined for the CC′ cross-section shown in Figure 4. The symbols at the surface show the data used to constrain it. The 3D structure was obtained from the correlation of 17 such sections.

Four 3D maps were drawn for the geometry of formations A+B, C+D, E+F and Bedrock. Figure 6 gives the depth of the crystalline bedrock relative to sea level, i.e, after subtracting topographic elevation. This allows to make a direct comparison with the results of BRGM shown in Figure 3.. The geometry in Figure 6 may seem similar to the BRGM model (Figure 3a), but differs in significant aspects. It has a trapezoidal rather than a syncline-shape geometry, at least for the central and eastern part of the basin (Raptakis et al., 2005). The deepest part of the basin occurs in its western part, S-SE of Lagada Lake with sediment thickness of about 400 m. This part seen in Figure 6 as lying inside the -300 m contour, is bounded to its west by the eastern edge of Lagada Lake, while in Figure 3a it is shown as a narrower zone extending below it. Moreover, according to BRGM model, in the central and eastern parts of the valley the bedrock occurs at depths of 100 to 120 m and less than 100 m respectively. However, in our model as seen in Figure 6, the bedrock depth is about 100 to 150 m at the central part of the valley and increases to 150 – 200 m west of Volvi Lake. In addition, the contours of the 3D model are broader near the edges of the valley as compared to BRGM model.

The site response of the Mygdonian basin was studied in terms of 1D empirical simulation. The resonant frequency map shown in Figure 7 was derived from the processing of single station microtremor measurements and the analysis of local and regional earthquakes recorded by the temporary accelerometer networks that have operated in the region (Euroseismod Final Report, 1999). The microtremor data were analyzed with the HVSR technique (Nakamura, 1989), while the earthquake data with three independent techniques: HVSR (Lermo and Chávez-García, 1993), SSR (Borcherdt, 1970) and GIS (Andrews, 1986). As can be seen in Figure 7, the lower frequency values (0.33–0.39 Hz) occur at the western part of the basin where sediments are thicker. This region is bounded by a zone of 0.4–0.6 Hz. Similar values occur at the eastern part of the basin, west of Volvi Lake where the sediments thickness is about 150–200 m. The dominant frequency at the central part of the basin lies around 0.61–0.75 Hz, while at the edges of the valley it increases significantly. Generally, the transition from low frequency values at the centre of the basin to high frequency values at the edges are inversely proportional to depth, as we expect for site response controlled by impedance contrast. The structure shown in Figure 6 was validated through comparison with the resonant frequency map of Figure 7. The excellent agreement between them shows that site response in the Mygdonian basin is controlled by the impedance contrast between sediments and bedrock. Previous analysis of the site response at Euroseistest have been based on the 1D and the 2D paradigms (e.g. Raptakis, 1995; Raptakis et al., 1998; Riepl at al., 1998; Chávez-García et al., 2000; Makra, 2002; Makra at al., 2005; Manakou et al., 2004; Raptakis et al., 2005). Those studies have shown the large impact that the complex subsurface structure has on ground motion. The 2D cross-section that was selected in the past has been very helpful to demonstrate the role of lateral irregularities in site response. The Mygdonian basin, however, is clearly a 3D structure and the selection of a particular cross-section was the best compromise that could be reached 15 years ago. In recent years we have seen the emergence of the study of 3D structures, avoiding past limitations. The permanent strong motion array in Euroseistest has been expanded to analyze the site response of the complete basin. The analysis of the data that is being recorded requires a reliable model of the subsoil structure. This paper is a contribution in that direction.

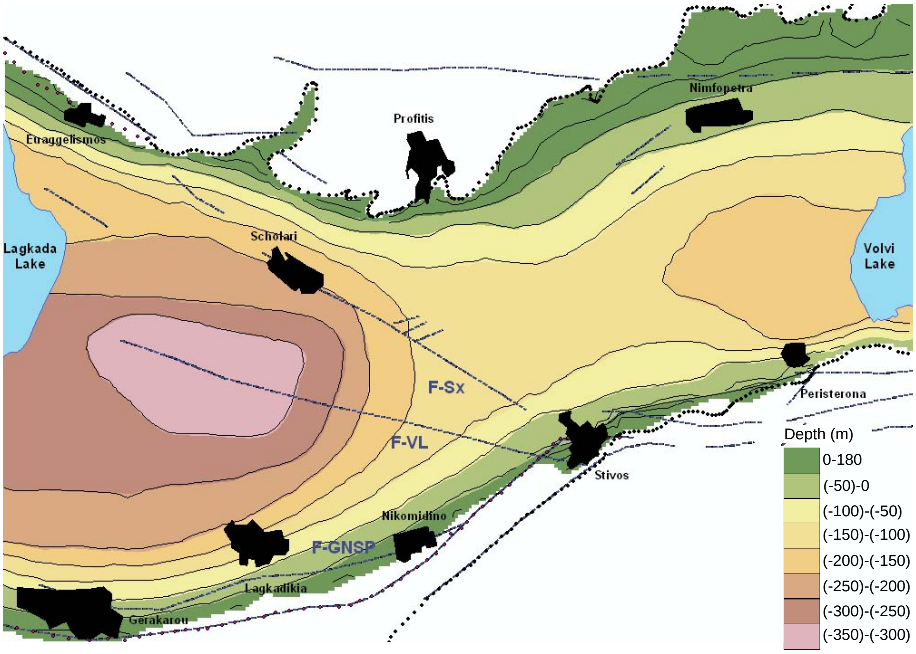

Figure 6. Contours (in m) of the geometry determined for the interface sediments-bedrock in this paper. Depth values are referred to the mean sea level.

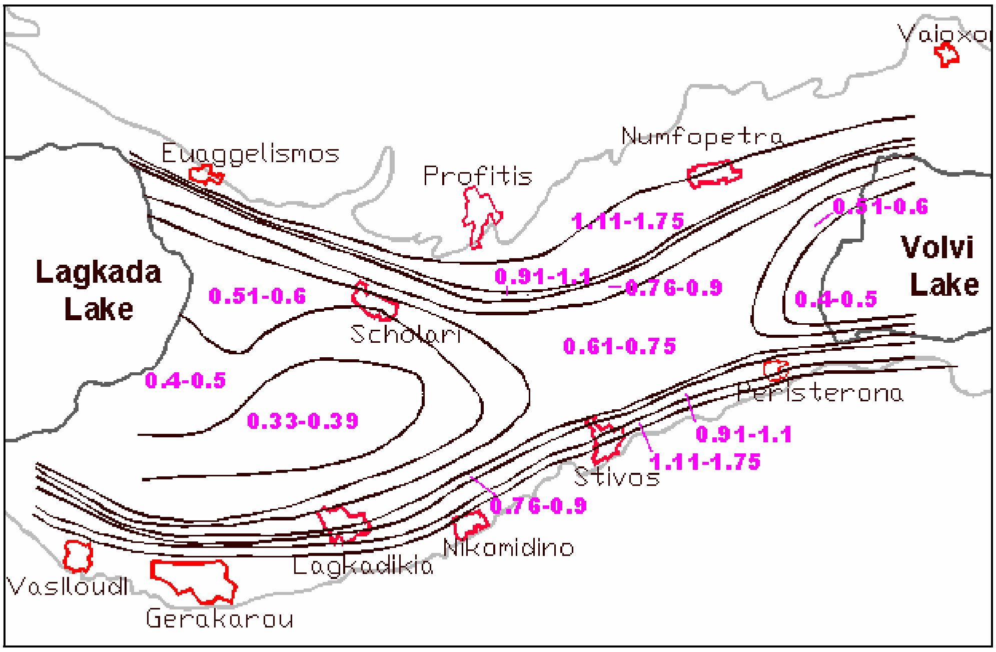

Figure 7. Contours of resonant frequency in Hz (Manakou et al., 2004).

CONCLUSIONS

We have presented the results of the synthesis of data from many different sources to constrain the 3D structure of the Mygdonian sedimentary basin. We started from the basin geometry derived from the exploration of the basin made by BRGM (1971). This structure was refined, and the mechanical properties of the materials determined, based on shear-wave velocity profiles measured at 29 sites within the valley. In addition, we used the data from the long (4 km) refraction profiles carried out during 2003 and 2004 experiments. Lateral correlation within the data was explored using 17 different 2D profiles across the basin. Each of these 2D cross-sections incorporated all data available in its vicinity (mainly geological and geotechnical). The correlation among all those 17 sections allowed us to draw maps that show the 3D geometry of the interface between sediments and the crystalline bedrock. In addition, the geometry of the interface between the Promygdonian and Mygdonian sedimentary systems could be determined with reasonable accuracy. Independently, dominant frequency contours on the free surface were drawn based on single station microtremor measurements, weak and strong motion earthquake recordings. The excellent agreement between this resonant frequency map and the geometry determined for the basement validates our results and shows that site response in the basin is controlled by the impedance contrast between sediments and bedrock.

Our results constrain the geometry and mechanical properties of a large part of the Mygdonian basin. This 3D model is a significant improvement on previous estimates based exclusively on dominant frequency measurements (Manakou et al., 2004), or on the measurement of electrical resistivity (Thanasoulas, 1983; IGME, 2001; Tournas, 2005). In contrast to those attempts, our current model reflects direct measurements of V_s at 31 sites within the basin (29 of them came from the array microtremor measurements, the rest from the two reverse refraction experiments of 2003 and 2004), in addition to previously available information. Therefore, our model has a closer relation to earthquake site response than previously proposed structures. We are convinced that our proposal is a reliable estimate of the geometry and the mechanical properties of the Mygdonian basin. As such, it provides a critical input to the simulation of its ground motion and to the interpretation of the earthquake records that are currently being obtained in the permanent strong motion array.

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