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Geophysical studies relating to the tectonic structure, geothermal fields and geomorphological evolution of the Sperchios River Valley, Central Greece

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ABSTRACT: *An integrated geophysical investigation including resistivity, gravity and SP measurements is used to reveal the overall tectonic status of the Sperchios River Valley, Central Greece, as well as the sedimentation of the valley at various depths in view of the geothermal status. Deep Schlumberger soundings are interpreted by 2D models and then used to constrain the density values in the corresponding gravity profiles. The combined interpretation of resistivity and gravity measurements suggests that the valley consists of deep sediments mainly of clayey origin and the valley fill reaches two kilometers beneath the Delta. The depth of the bedrock (which has ophiolite or flysch and limestone underneath) is controlled by some buried faults mainly of E-W strike. Other faults of NNW-SSE strike create some sinkings and uplifts in the bedrock relief. The interpretation of geophysical data verifies blocky shaped bedrock. Such a fault system in the southern part of the valley is also related to geothermal surface manifestations. Faults in the flysch give rise to a deep passage for geothermal fluids which reach the surface through geothermal circulation zones in the sediments detected by the SP method. The deposition of the Sperchios River and its torrents, and the tectonic activity (sinkings and uplifts in the bedrock detected by the whole geophysical survey), mainly affect character of the sedimentation (shown by resistivity interpretation) and river routes.*

INTRODUCTION

The Sperchios River Valley is of great geological interest due to the intense tectonic activity (steep slopes with high mountains around the valley), the presence of geothermal sources in many places, and the intense and fast deposition of the river, which has created a vast delta.

The exploitation of the geothermal field, the constructed dam in the area of the tributary river Vistritsa, and the future plan for an underwater tunnel in the Maliakos Gulf for the national highway, as well as the agricultural catastrophes that ensued after the river burst its banks, are all aspects that indicate the economic interest in the valley.

The issue of greatest interest is the fault system mostly covered by the deep sediments which lie throughout the valley. This system could explain the geothermal status, the process of the valley's occurrence and the probable connection with nearby big faults (such as the Anatolia Fault or the Atalanti Fault). Some theoretical models regarding the tectonic activity of the area already exist (Mariolakos, 1976, Dermitzakis and Papanikolaou, 1979) but contain no specific data describing the position of the faults underneath the deep sediments.

The existing drillings are terminated in shallow depths. Some problems arising from the geology of the area can be solved by geophysical methods. Schlumberger resistivity soundings can give valuable information regarding with the deep sedimentation while gravity and SP methods could solve problems related with deep rock formations and geothermal fluid circulation zones, respectively.

GENERAL GEOLOGY

The Sperchios River Basin is in Central Greece (Fig. 1), surrounded by Orthris, Timfristos, Vardousia, Iti and Kallidromo Mountains. The Basin opens to the sea in the East at the Maliakos Gulf. The Sperchios River runs from W-E. Among many other, the most important tributaries, from the West to the East, are Roustianitis, Vistritsa, Gorgopotamos, Xirias and Asopos.

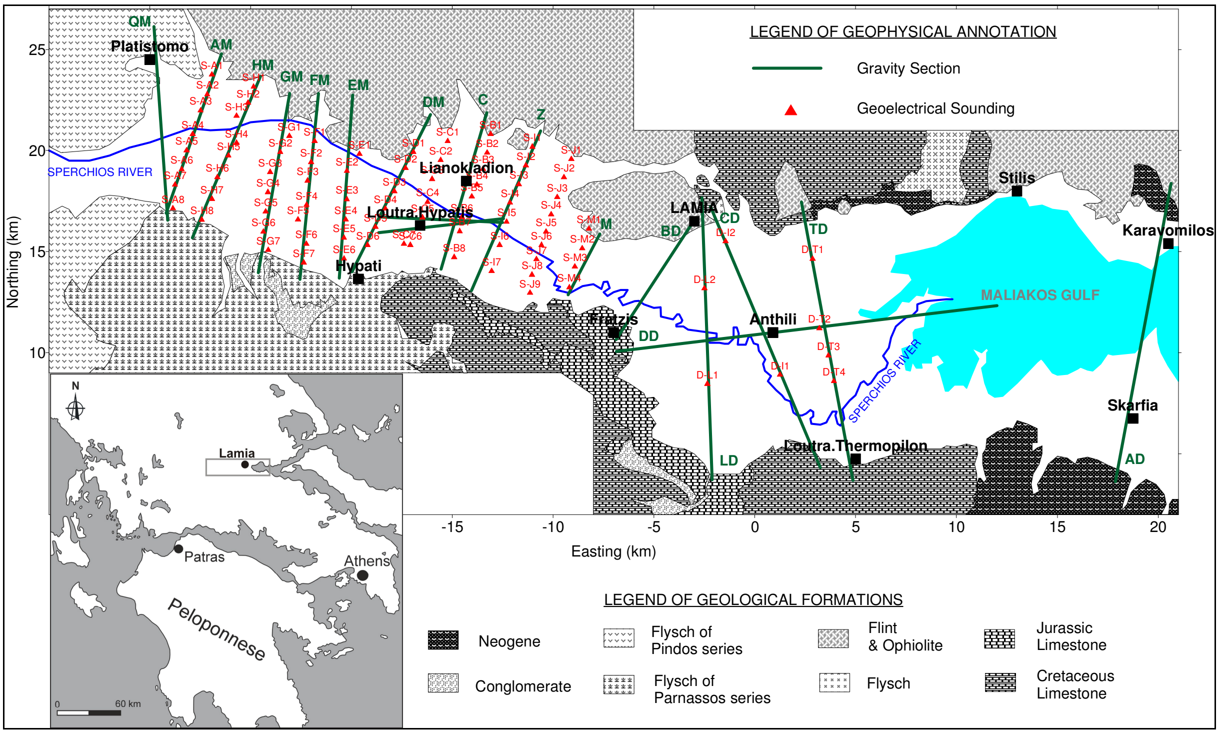


FIG. 1. The geological map and the geophysical survey of Sperchios River Valley. (The position of the deep resistivity Schlumberger soundings and the sections after interpretation of gravity profiles is shown). The small map shows the area under investigation in Greece.

The Sperchios River valley is a result of a tectonic graben and lies in the transition area from the inner to the outer geotectonic zones. The Basin is divided into two parts: the Inner Valley and the Delta of the Sperchios River. The geological map of the Valley, compilation result of IGME geology maps (Marinos et al, 1963, 1967 and Kalergis et al, 1970), is shown in Figure 1.

Alpine Formations

North-by-north-east of the basin there are limestones, flints and ophiolites dating from the Triassic to the Jurassic periods. North-east of Lamia, there are Upper Cretaceous transgressive limestones and flysch. The same patterns are observed in Kallidromo Mountain, south-east of the basin. The areas previously considered belong to the "East Greece Series" that is made up of some paleotectonic series that have been homogenized by the Upper Cretaceous transgression (Papanikolaou, 1986). Such series in the area under investigation are the "Maliaki" and "Hypopelagoniki" series. The "Parnassos" series is in the southern part of the basin, in Iti Mountain, where there are Cretaceous limestones and flysch. The "Pindos" series, where limestones and Jurassic flysch dominate, is in the western part of the basin.

Sediments

The tectonic graben forming the basin consists of loose deposits of great thickness. These are

- Oligomiocene conglomerate
- Pleistocene lacustrine deposits (conglomerates, sands and clays) under the alluvial deposits of the Sperchios River
- Alluvial deposits of the Sperchios River (clays with intercalations of conglomerates and fanglomerates).

Tectonic Activity of the Sperchios Graben

The irregular topography (the steep slopes of Oeti and Kallidromo Mountains, at least two river terraces, the displacement of river sill and many alluvial fans) is the consequence of high tectonic activity (Dermitzakis & Papanikolaou, 1979) (Figure 2). An interpretation of this activity is the theory of the tectonic dipoles (Mariolakos, 1976) as shown in Figure 2.

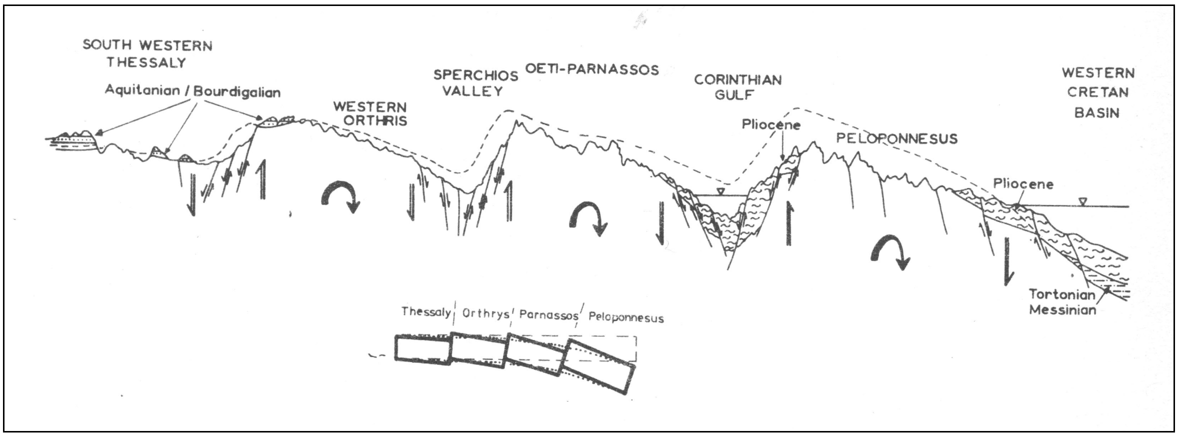


FIG. 2. The tectonic activity in Central Greece and Peloponnese (Dermitzakis & Papanikolaou, 1979) and an interpretation of it with tectonic dipoles of Mariolakos (1976).

By inspection of aerial photographs, Muhlfeld (1975) observed faults of a W-E direction that define the sinking of the valley and some faults of a NNW-SSE direction that have created rearrangements in the stratigraphy of the alluvial deposits.

The geophysical survey (Figure 1) consists of a) resistivity survey with deep Schlumberger soundings (AB/2=3000m), b) a gravity survey, and c) a self-potential (SP) survey in the area of Loutra Hypatis. All data were processed and interpreted in order to determine the depth of the bedrock, some intermediate layers, existing faults, and the hot water circulation zones in the sediments (with SP survey). The results of geophysical surveys have already been presented for the two parts of the Basin (Apostolopoulos 1993, 1994, 1995). This paper attempts an integrated interpretation (with some new interpretation techniques) in order to present the overall tectonic status in relation with the evolution of the valley and the geothermal activity of the region.

Resistivity Survey

Figure 3 shows the apparent resistivity maps of certain half current electrode distances (AB/2). These maps give an outline of the lateral resistivity distributions at certain approximate depths. The map of Figure 3a (AB/2=100 m) shows large areas of high resistivity values in the western part of the valley caused by the resistive layer of conglomerate created by the action of the Vistritsa River, and southwards of Loutra Hypatis, due to the presence of a hill of limestone. The conglomerate layer still has a significant influence on the mapping in Figure 3b (AB/2=464 m) indicating a great thickness value for this layer. Both maps (Figures 3a, 3b) show relatively high values near Lamia city caused by the ophiolite body at the surface. The presence of the resistive bedrock affects the contours in the maps of Figures 3c and 3d (AB/2=1000 m, 2154 m), where bedrock sinkings (in the area of Lianokladion) and uplifts (in the area of Lamia-Frantzis) are observable, most probably caused by faults. The change in the route of the Sperchios River going south follows the shape of resistivity contours (south-eastern part of the map in Figure 3d) that indicate the presence of a fault approximately of a north-south direction. The region southwards of Lamia city has relatively high apparent resistivity values.

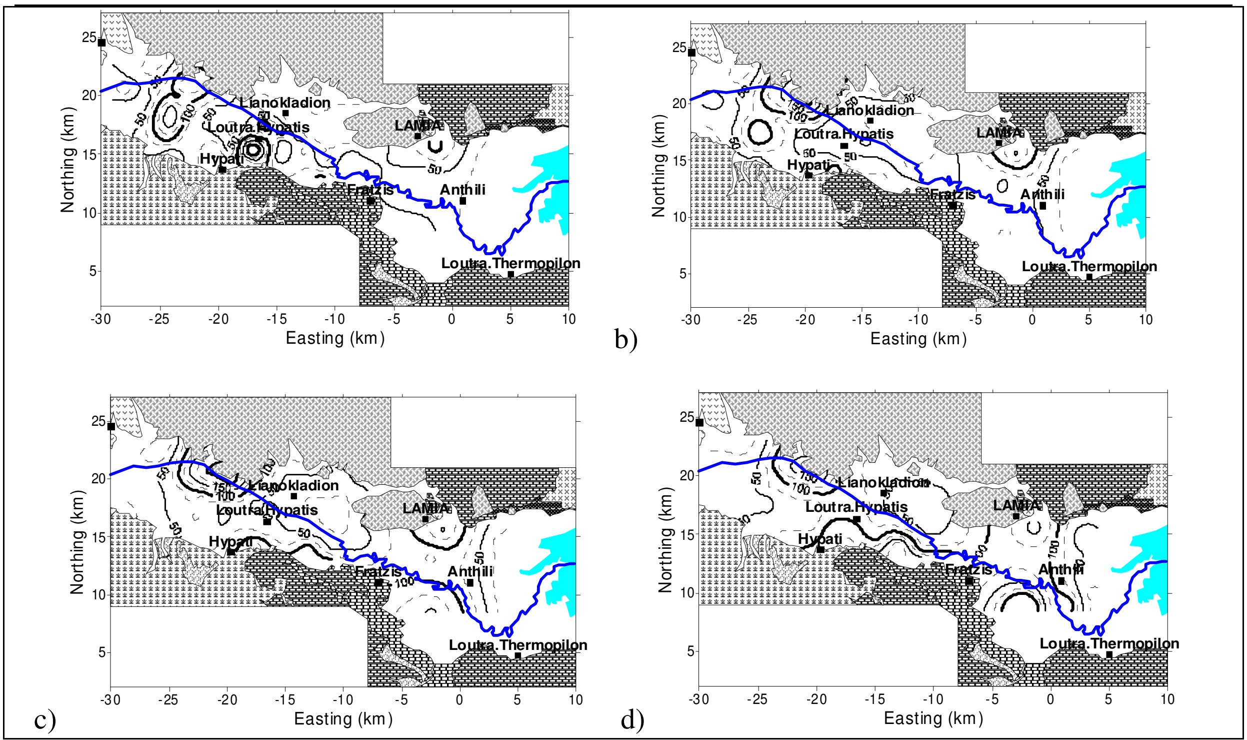


FIG. 3. Apparent resistivity maps (contours in ohm-m) of certain half current electrode distance (AB/2) a) 100m, b) 464m, c)1000m and d) 2154m.

Schlumberger soundings on surface manifestations of rock formations gives the resistivity values of ρ_{flysch}=80-180ohm-m, $\rho_{ophiolite}$=200-600ohm-m, and $\rho_{limestone}$ =250-1100 ohm-m) in the area under investigation for flysch and limestone.

A 2-D interpretation technique (Apostolopoulos, 2003) is applied in the semilogarithmic apparent resistivity section of each profile, resulting in a 2-D picture of the underground with sequences of layers geoelectrically defined. Figure 4b shows the resistivity model after 2-D interpretation for the profile “G”, with Figures 4a and 4c showing sections of the observed apparent resistivity values and those calculated by the model. The presence of a fault in the bedrock under sounding “G3” and the surface resistive conglomerate due to the action of the Vistritsa River between soundings “G3” and “G6” are evident in the resistivity sections. The great thickness of conglomerate ($\rho_{con} \cong 140$ ohm-m) shown in Figure 4b was already concluded by the qualitative interpretation of the apparent resistivity maps.

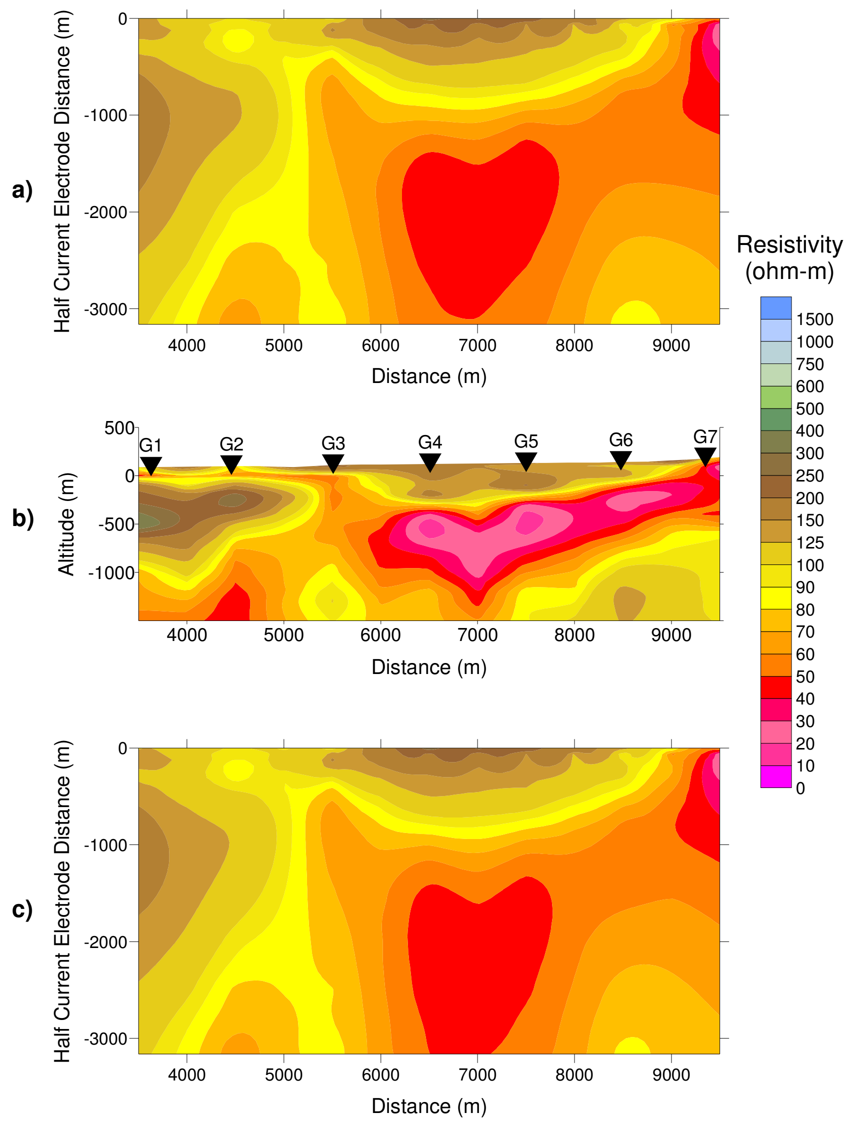


FIG. 4. G profile: 2D resistivity interpretation of the observed apparent resistivity section (a) with the final model (b) giving similar to the observed calculated apparent resistivity section (b). A deep surface resistive layer with a clay layer underneath followed by flysch. The ophiolite in the northern side is near the surface.

The same procedure was followed in all resistivity profiles. The results of 2D resistivity interpretation for all Schlumberger profiles in the Inner Valley (western part) are shown in 3D (the underground in slices of resistivity distribution) in Figure 5. All slices down to a depth of 300 m show a high resistive layer in their north central part, representing ophiolite. The top four slices show the conglomerate resistive layer detected in the “G” profile to be to the left of the ophiolite. The presence of conglomerate in the western part pushes the river northwards which turns southwards as it approaches the sinking bedrock in the east. Low resistivity values represent clay sediments with flysch underneath gradually resembling the northern part as we go deeper. A very important feature is the presence of flysch in the middle part of the area at medium depths with the clay sediments that are presented on both sides. Finally, the high resistive layer, down to a depth of 500 m, in the southeast part, is possibly limestone.

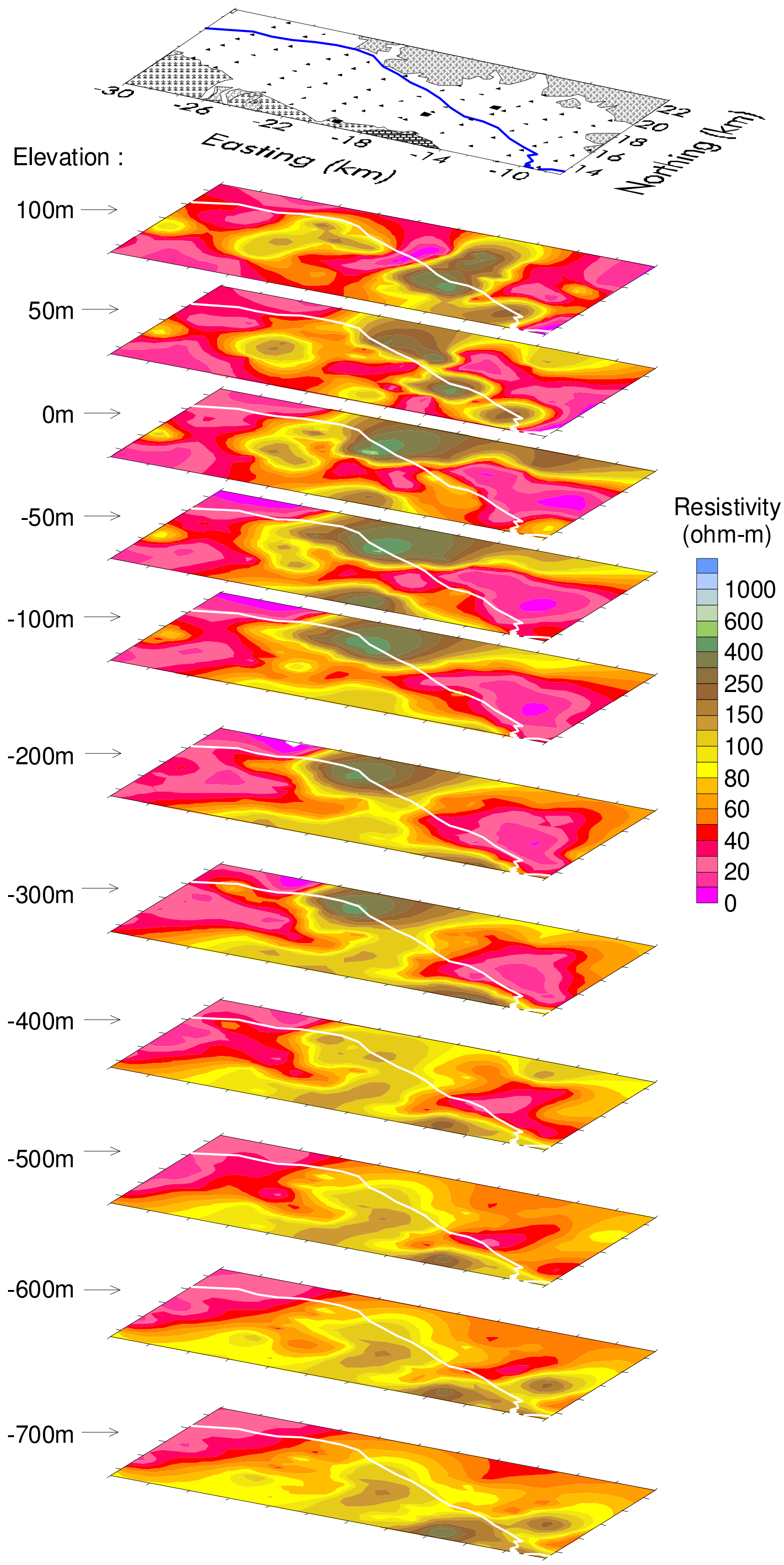


FIG. 5. 3D picture of the underground of Inner Valley in slices of resistivity distribution.

There is a clear correlation between apparent resistivity maps (Fig. 3) and the 3D resistivity representation of the underground (Fig. 5).

The results of resistivity interpretation are used in the gravity interpretation to constrain the depths of interfaces: sediments - flysch, flysch-limestone (very deep) and ophiolite-flysch (in the northern part of the valley).

Gravity Survey

The gravity data are acquired along lines nearby the resistivity profiles. The regional anomaly, to be excluded in 2D interpretation for each profile, was estimated using the Gravity Map of Greece 1:500.000 scale (Lagios, 1988) in the direction of the profile (Fig. 6a).

In order to see the residual map of the whole area, a good approximation of regional anomaly (comparing with the gravity map of Fig. 6a) is acquired using the gravity data in this area and finding their first-degree trend (Fig. 6c).

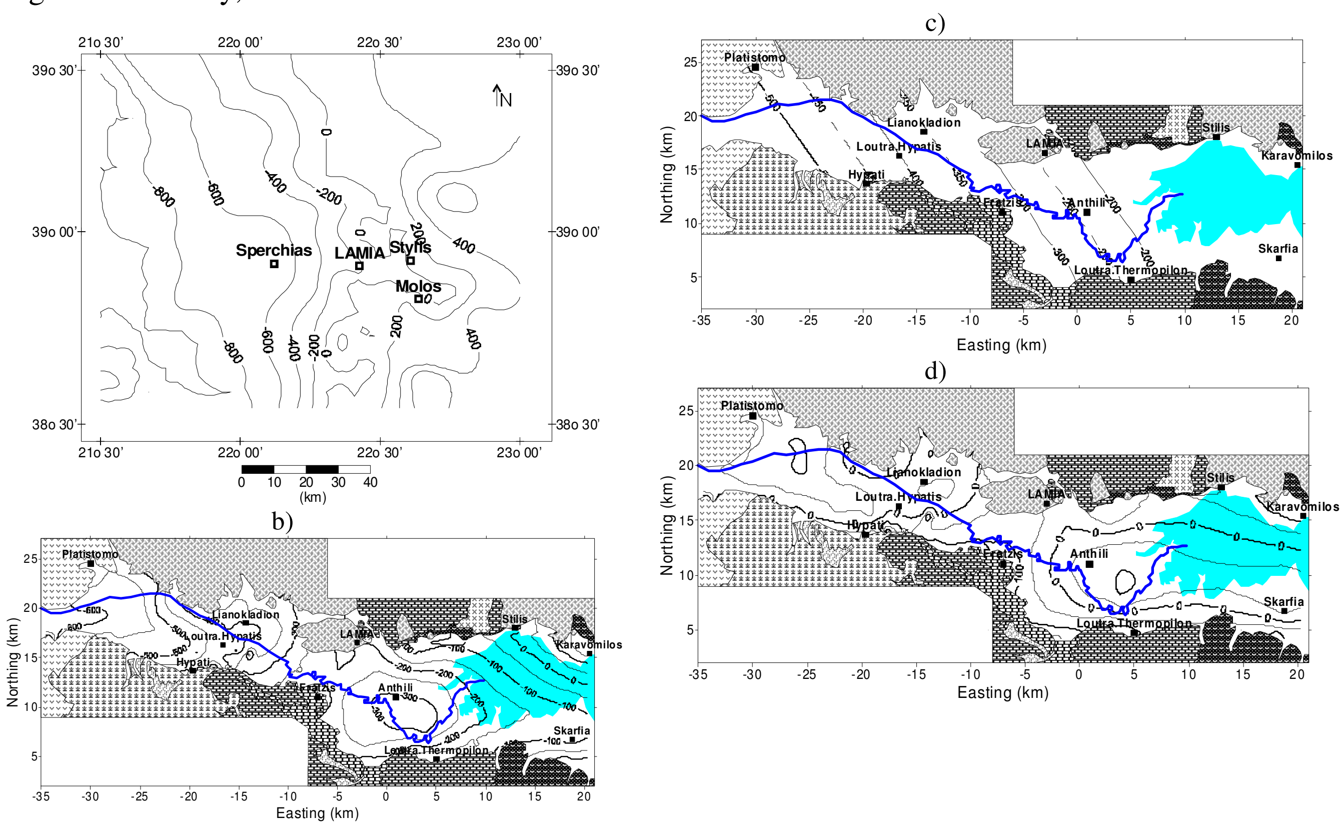


FIG. 6. a) Part of Gravity anomaly map of Greece (Lagios, 1988), b) Bouguer c) Regional and d) Residual Gravity Maps (contours in gu)

The Bouguer map of the area (Fig. 6b) and more clearly the residual map (Fig. 6d), after the reduction of the regional anomaly (Fig. 6b), give an idea of the bedrock relief. There is a clear similarity between apparent resistivity map and the corresponding gravity map (AB/2=2154 m). Both maps also suggest that the bedrock has two sinkings on both western and eastern sides of the Inner Valley (south-east of Platystomo and near Lianokladion). The presence of these two sinkings will be discussed later. Another sinking of the bedrock is near Anthili in the Delta. There is uplift in the bedrock in the area of Lamia and Frantzi that has been observed in the deep apparent resistivity maps as represented by high apparent resistivity values. The probable north-south fault in the route change of the Sperchios River is evident but it is more certain and significant that the faults in the area east of Anthili and in the Maliakos Gulf have an east-west strike.

Density measurements on rock samples helped in the lithological definition of the gravity layers. The 2D gravity interpretation by depth constraints derived from the apparent resistivity data gave the depth of the bedrock and the position of the existing faults. An example is the gravity profile "GM", where the presence of the dense layer of conglomerate near the surface, outlined by the apparent resistivity data, gave necessary information for the gravity interpretation. The final model is shown in Figure 7.

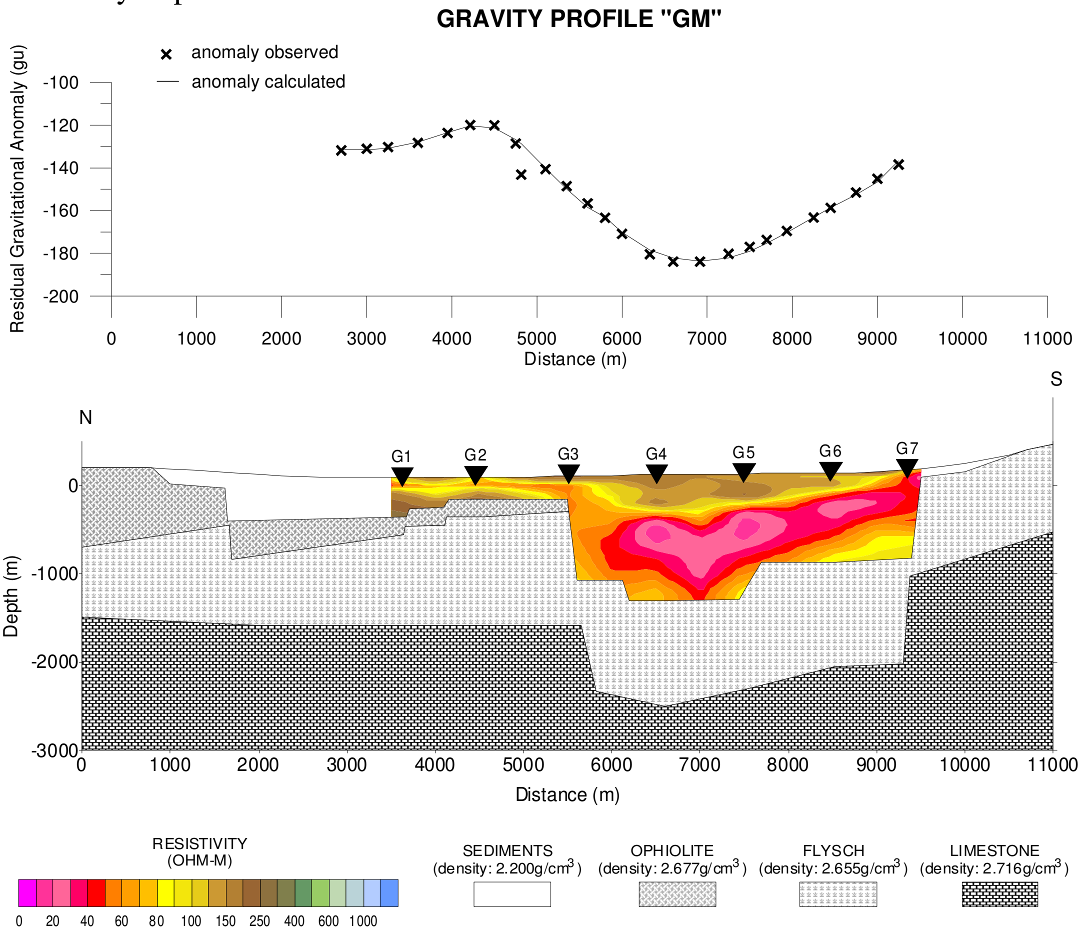


FIG. 7. 2D interpretation of gravity profile "GM" with the resistivity and gravity model both present.

Gravity interpretation detected the presence of a fault under sounding "G3" and bedrock sinkings caused by other faults has been detected by the interpretation of the gravity and apparent resistivity data.

This procedure proved valuable since resistivity interpretation gave information about the extent of the dense surface conglomerate layer (a result mainly of river activity) that makes substantial contribution to the gravity data. The detection of other geological interfaces by resistivity interpretation produces fewer parameters that cause variation in the gravity data. The interpretation of the apparent resistivity data also helps to the detection of the bottom of a flysch body and the top of the underlying limestone.

The same procedure was followed throughout the surveyed area with gravity profiles and depth constraints derived from the resistivity interpretation. In the Delta area, the thick fine clay material of the sediments limits the depth of investigation of the resistivity soundings and only permits to determine the existence of very few horizons useful for gravity interpretation. The gravity profile "AD" had no resistivity data and the interpretation considered just one horizon that consists of the bedrock (Fig. 8).

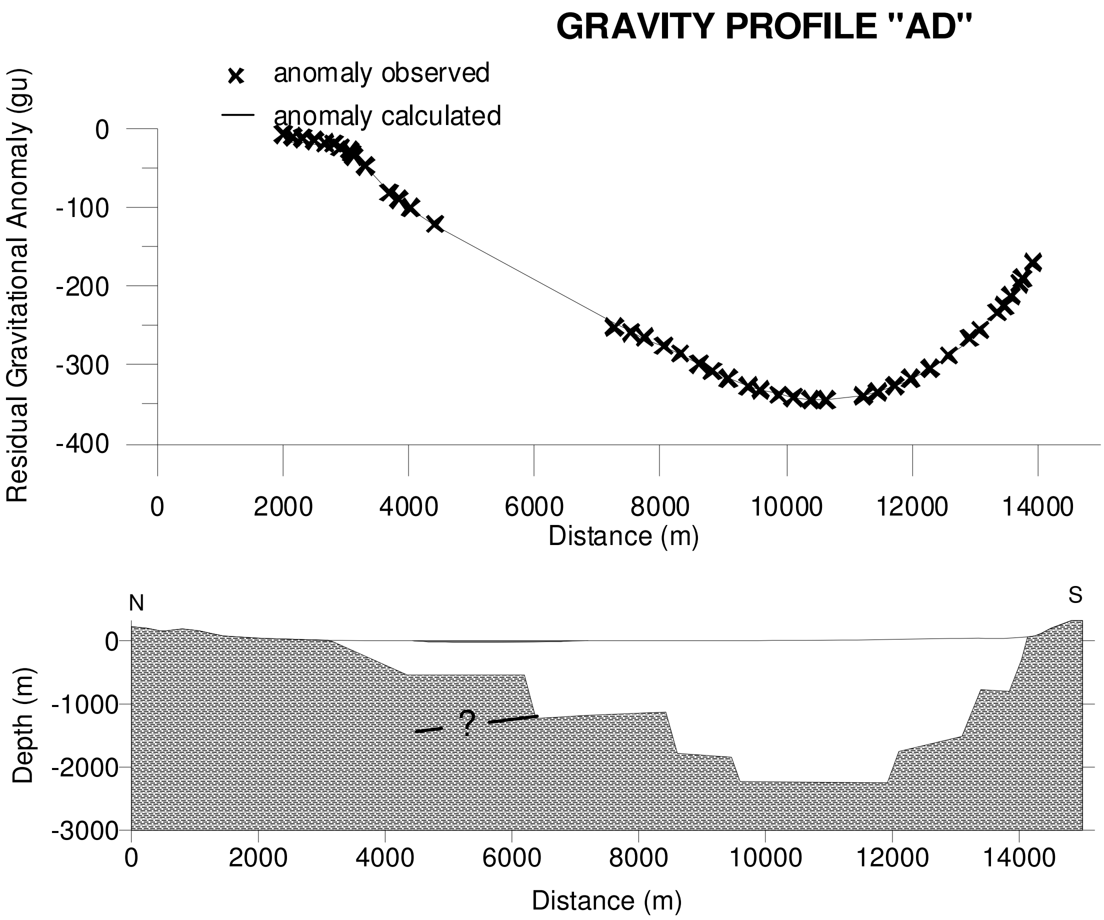


FIG. 8. 2D interpretation of gravity profile "AD" with densities of bedrock 2.714g/cm^3 and sediments 2.2 g/cm^3.

The magnetic map (IGME) of the Sperchios River Delta (Fig. 9) can qualitatively indicate the presence of ophiolites, in which the contour 75 gamma indicates an outer bound of them.

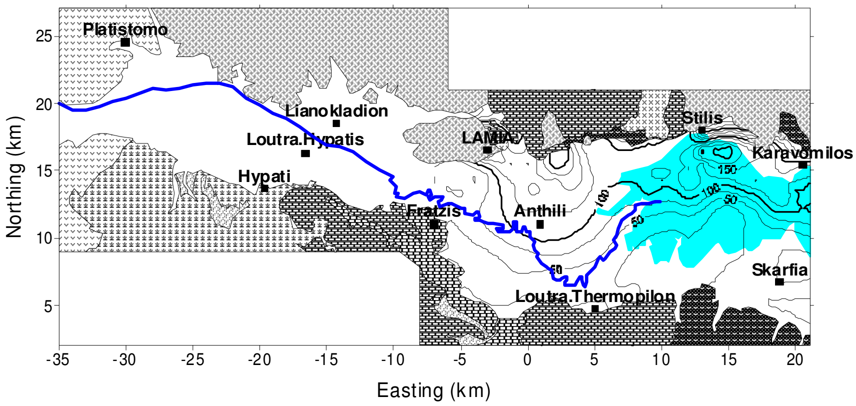


FIG. 9. The Magnetic map (Residual Anomaly) of Sperchios River Delta (IGME) (contours in γ)

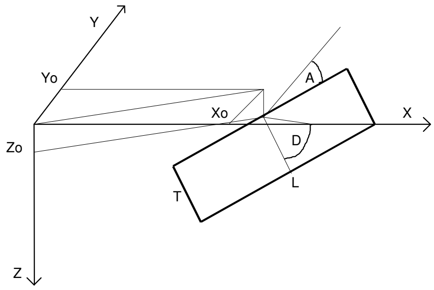
Therefore, the deep bedrock at distances between 0.0 m to 6500 m in the gravity model of profile "AD" (Fig. 8) is ophiolite and beyond this distance there is a sinking of the bedrock caused by faults.

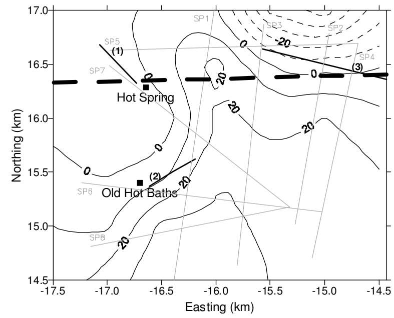
Self-potential Survey

A self-potential survey in the area of the Loutra Hypatis hot medical baths was designed to detect the local geothermal field. A hot spring supplies the medical baths with decreasing production.

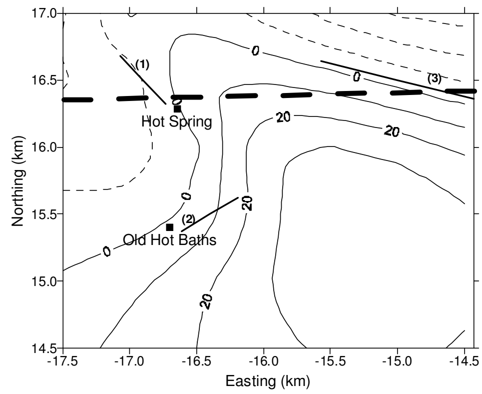
The total field electrode configuration and the electrode polarization monitoring together constituted the SP field data acquisition technique (Apostolopoulos and Lagios ,1993, Apostolopoulos et al., 1997).

The SP map in the area of Loutra Hypatis (Figure 10b) was interpreted using 3-D modelling (Fitterman, 1984, Fig. 10a) which outlined hot water circulation zones.

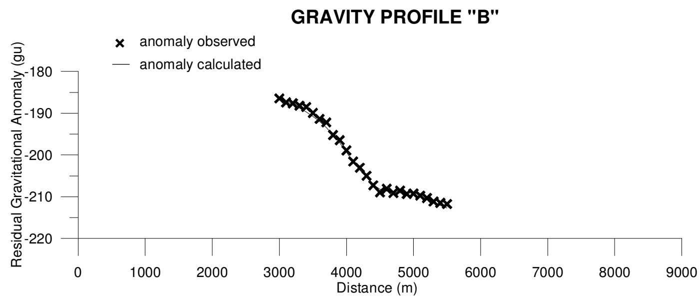




b)



c)



d)

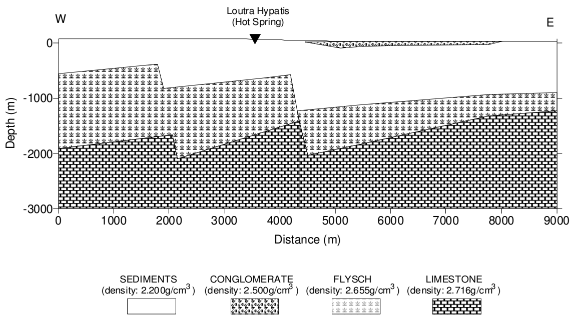


FIG. 10. Self potential survey in the area of Hypati Hot Spring with measured SP data (b) hot spring circulation zones derived from the interpretation of 3D model (a) that produce the SP computed map (SP profiles with gray lines in SP observed map). Nearby gravity profile (dashed line in SP maps) gives the overall structure of the underground with faults and blocks of flysch that is underlined by limestone.

Table 1. Model parameters of hot water circulation zones.

Zone	F_O (mV)	X_O	Y_O	Z_O (m)	T (m)	L (m)	D	A
(1)	-45	-16.9	16.5	50	1250	1500	61.5^o	136.8^o
(2)	-60	-16.4	15.5	195	1250	750	85.6^o	238.4^o
(3)	-447	-15.0	16.5	455	1000	1170	83.4^o	284.9^o

The model parameters of this interpretation are given in Table 1. The synthetic SP map shown in Figure 9c is the model response of these zones and it is quite similar to the observed one.

The SP detected circulation zones in the sediments (with more or less uniform resistivity) supply hot waters drained by deeper faults of the flysch detected by the gravity survey, profile “B” (Fig. 10d), under the area of the Hypati Hot Spring. Circulation Zone “1” is near the hot spring at the surface. Recent drillings near circulation zone “2” were quite productive, in an area referred to locally as “old hot baths”. Zone “3” is deep, more probably related to a flysch fault (lateral resistivity change) and hot water circulation zone. The deep production drilling near Zone “2” is now providing the medical baths with hot water.

DISCUSSION – RESULTS OF THE GEOPHYSICAL SURVEY.

The combination of all gravity interpretation results is supported by those of resistivity method. A picture of the bedrock relief is shown in 3-D model in Figure 11 and in 2-D mode in Figure 12 where all faults detected by geophysical interpretation.

The contours of bedrock depth (Figs. 11, 12) show a similar pattern with the apparent resistivity map (Figure 3d) and the residual map (Figure 6d). This similarities confirm the results of the integrated interpretation.

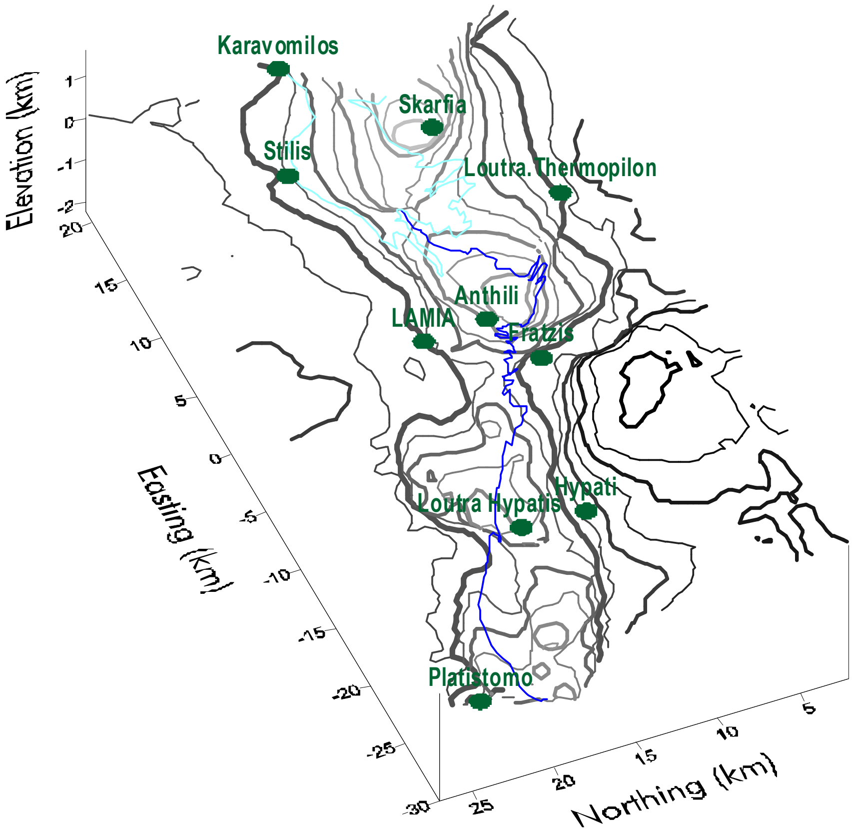


FIG. 11. The bedrock relief in a 3D mode of Sperchios River valley after gravity and resistivity interpretation.

The detected faults have in general an E-W strike with fault "F1" (Figure 12) being the north edge of the Sperchios trench and faults "F3"causing the very deep sinking of bedrock in the Delta southwards.

Some faults of N-S strike ("F4", "F5" in Fig. 12), as Muhlfeld (1975) also stated, have been delineated by geophysical interpretation. These faults cause the uplift and sinking of the bedrock as previously mentioned. The bedrock subdivided into some tectonic blocks, for example, as gravity interpretation shown in Figure 10d. Big tectonic blocks are formed by the southerly fault system "F2" (Figure 12) and affect mainly the uplift-sinking phenomenon.

This fault system "F2" is probably also related to geothermal surface manifestations (Fig. 12). Geothermal fluids from deep horizons pass through this system "F2", through the N-S faults near Loutra Hypatis and finally through the geothermal circulation zones in sediments, detected by the SP method, before reach to the surface.

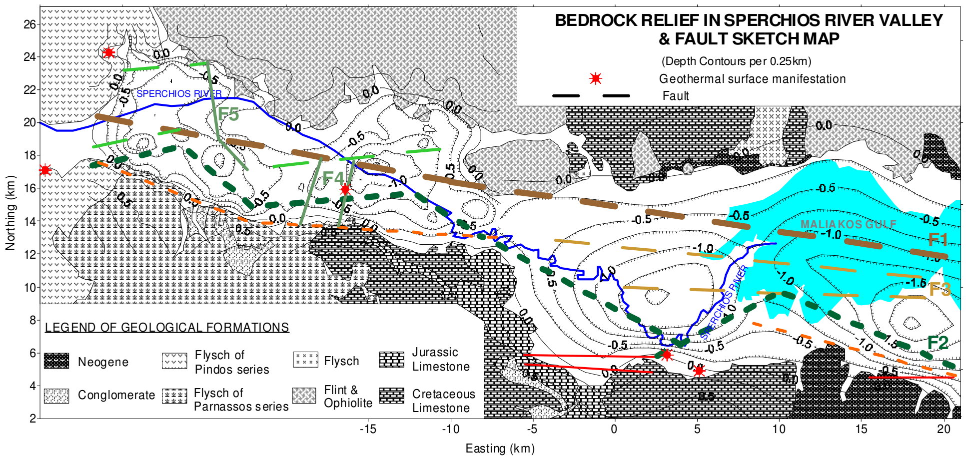


FIG. 12. The bedrock relief in a 2D mode of Sperchios River valley with all detected faults after gravity and resistivity interpretation.

Areas of conglomerate of great thickness are due to river action (e.g. Vistritsa river) (Figs. 3b, 3c, 4a and 5). The great thickness of the conglomerate layer in the area of the Vistritsa River indicates the great rate of fluviatile deposition that directs the river flow to the North. Consequently, the tectonic features and the sinkings of the bedrock influence the route of Sperchios River. Resistivity interpretation (Fig. 5) also shows, near the surface, that resistive coarse material and fine material of low resistivity are deposited above the sinkings of bedrock and the uplifts, respectively.

This integrated geophysical survey gives valuable information about deeply buried features for further research related to tectonic, geothermal, hydrogeological and geotechnical issues. Constructions such as a dam in the area of the tributary river Vistritsa should take into consideration the detected thick conglomerate layer and the nearby faults, as well as a future underwater tunnel planned to be built in the Maliakos Gulf for the national highway the E-W nearby faults. The features detected in the geophysical survey can better facilitate the design of microseismic survey to define active faults. The location of new production drillings for further geothermal exploitation should be better delineated by the geophysical results. Most importantly, the detected fault system may trigger some earthquakes in the future then some further research is necessary in view of the tectonic issues.

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REFERENCES

Apostolopoulos, G., 1993, Geophysical studies in the Sperchios basin: Ph.D. Thesis, Geology Department, University of Athens.

Apostolopoulos, G. and Lagios, E., 1993, Reconnaissance geophysical studies of Hypati Hot Spring in the Sperchios River Basin: 2nd Congress of Hellenic Geophysical Union, Florina, Macedonia, Greece.

Apostolopoulos, G., 1994, Geophysical Investigation in the Delta of Sperchios River: Bulletin of the Geological Society of Greece vol. XXX/5, 45-51.

Apostolopoulos, G., 1995, Geophysical investigation in the "Inner" valley of Sperchios River: Proceedings of the XV Congress of the Carpatho-Balkan Geological Association., Athens, pp.1103-1108.

Apostolopoulos, G., Louis, I., and Lagios, E., 1997, The self-potential method in the geothermal exploration of Greece: Geophysics **62**, 1715-1723.

Apostolopoulos G., 2003. Combined Sschlumberger and dipole-dipole array – 2D approach in resistivity interpretation: Extended Abstracts of 9th European Meeting of Environmental and Engineering Geophysics, Prague, Chech Republic.

Dermitzakis, M. and Papanikolaou, D., 1979, Paleogeography and geodynamics of the Aegean Region during the Neogene: VII Int. Congress Medit. Neogene, Athens, Ann. Geol. Pays Hellen hors serie IV, 245-289.

Fitterman, D.V., 1984, Thermoelectrical self-potential anomalies and their relationship to the solid angle subtended by the source region. Geophysics **49**, 165-170.

IGME, Aeromagnetic maps of Central Greece.

Kallergis, G., Koch, E. and Nicolaus, H., 1970, Geological map of Greece, "Sperchias" sheet, scale 1:50000. I.G.M.E., Athens.

Lagios, V., 1988, Gravity anomaly map of Greece, a recompilation: IGME.

Marinos, G., Anastopoulos, J., Maratos, G., Melidonis, N. and Andronopoulos, B., 1963, Geological map of Greece, "Stylis" sheet, scale 1:50000. I.G.M.E., Athens.

Marinos, G., Papastamatiou, J., Maratos, G., Melidonis, N., Andronopoulos, B., Tataris, A., Betoulis, D., Katsikatsos, G., Maragoudakis, N. and Lalechos, N., 1967. Geological map of Greece, "Lamia" sheet, scale 1:50000. I.G.M.E., Athens.

Mariolakos, I., 1976, Some thoughts and aspects on certain problems of the geology and tectonism of Peloponnese: Ann. Geol. Pays Hellen **27**, 215-313.

Muhlfeld, R., 1975, Study on Linear Tectonic structures in the Sperchios Valley. As seen on Actiae Photographs: **4**,1-4,Hannover.