

QUANTIFICATION OF HUMAN IMPACT ON NATURAL EVOLUTION PROCESSES AT A COASTAL ZONE, ADJACENT TO AN ACTIVE FAULT

J.D. ALEXOPOULOS¹, EMM. VASSILAKIS¹, S. DILALOS¹ and E. ZALOUMI¹

¹National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, Panepistimiopolis, 157-84, Athens, Greece.
E-mail: jalexopoulos@geol.uoa.gr

EXTENDED ABSTRACT

A coastal management study at areas with steep anaglyph requires detailed knowledge of the onshore surface and subsurface regime regarding the erosional procedures. Active faults produce dynamic and continuously evolving geomorphological structures, which require investigation and continuous monitoring. Detailed mapping on and adjacent to these surfaces is required in order to study the complexity of various tectonic discontinuities, which contribute significantly to erosion and rock-falls resulting rapid and significant changes on the landscape. The technology of ground-based Light Detection and Range (LiDAR) capturing devices is a powerful and valuable tool, providing detailed mapping and surface change detection of inapproachable and nearly vertical surfaces.

In this paper we introduce the diachronic monitoring and detection of alterations on the surface of the shore-side active fault of Psatha (Greece), with terrestrial LiDAR scanning, for a state of the art mapping of the almost vertical limestone fault surface. The monitoring procedure includes high-detailed topographic survey at the adjacent area using Real Time Kinematics Global Positioning System equipment (RTK-GPS), which is consisted of a large pile of brittle debris, laying on top the fault surface, by the sea.

The described methodology involved the production of a high resolution DEM based on historic topographic maps (scale 1:5,000) of the regional area and comparing it with the higher resolution DEM representing the contemporary morphology, produced by the combination of the fault wall LiDaR "point cloud" and the dense grid of the RTK-GPS measurement points. The comparison between these datasets and recently acquired high resolution IKONOS satellite images revealed impressive surface changes caused mainly by the human intervention as well as the erosional processes which were accelerated due to the absence of safety measures along the coastal zone.

Furthermore, the regional subsurface of the hanging wall zone area was also investigated, especially underneath the brittle debris formation, applying the high-resolution near surface geophysical technique of Electrical Resistivity Tomography (ERT). Several sections were conducted aiming to represent the subsurface extension of the visible structures in three dimensions and combine it with the aforementioned datasets.

The successful combination of different techniques revealed and quantified the landscape evolution involving the surface alternations at the fault adjacent coastal zone, the sea intrusion and even the coastline displacement, during the last four decades. Most of these yielded to the anthropogenic interference on the brittle debris formation and even the construction of the coastal road.

Keywords: surface change detection, terrestrial LiDAR, electrical resistivity tomography, remote sensing.

1. INTRODUCTION

The area of interest is located at the easternmost coastal zone of the Corinth Gulf in Greece (see Figure 1). Psatha Bay is one of the most seismogenic regions which hosts

neotectonic faults that have been recently activated (1981) and produced disastrous earthquakes (Morewood & Roberts, 1999). Many of these neotectonic structures surround the bay and create steep coasts (Mariolakos & Fountoulis, 1998), which in many cases are difficult to be reached and studied in high detail. The coastal zone along the Psatha active fault escarpment was chosen for developing a multi parametric methodology involving high resolution remote sensing and near surface applied geophysics techniques, in order to gain detailed knowledge of the onshore surface and subsurface regime regarding the erosional procedures.

The foot wall consists of Triassic-Jurassic limestones and thick Pleistocene debris covers the hanging wall (Theodoropoulos, 1968). Along the sub-vertical fault scarp various tectonic kinematic features reveal several displacements during the post-alpine period causing a total visible throw of 185m and forming a steep coast. This activity produces a dynamic relief, which continuously alters the coastal zone that is also suffering the human intervention for more than the last two decades.

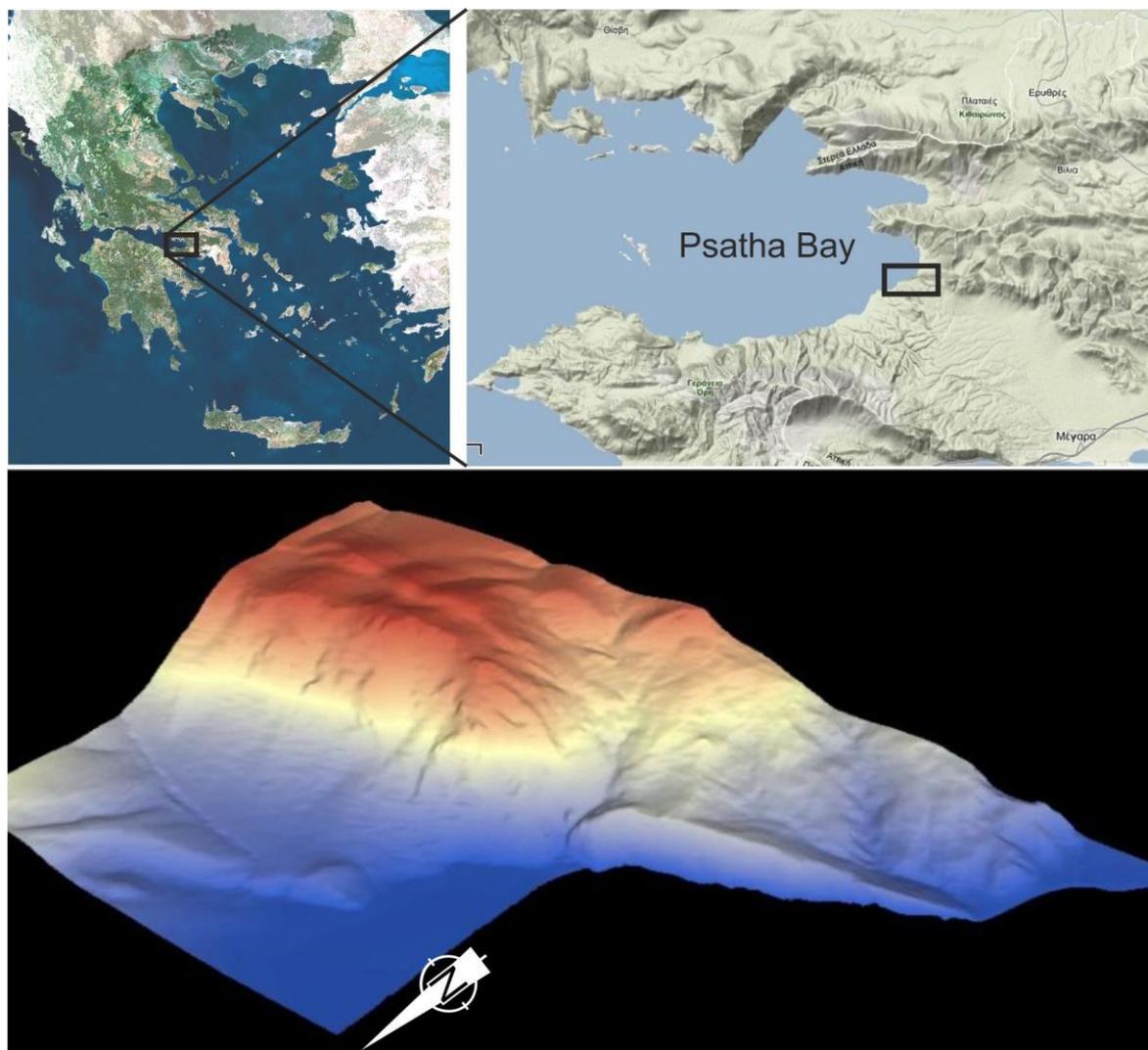


Figure 1. Index map of the study area and high resolution painted shaded relief of the coastal area (below).

2. METHODOLOGY

2.1. Topographic surveying

The high relief of coastal area required a combination of several surveying methods for succeeding high accuracy topography at the largest possible scale. Initially an establishment of a local control network was designed, which comprise the basic reference for different kind of measurements. This network consists of three base stations (SG-1, SG-2, SG-3), which were selected based on the visibility of the entire coastal area, especially at places where the debris are cropping out. The stations were also used for setting up the laser scanning procedures (see Figure 2). This part of the surveying was held with Global Positioning System (GPS) – Static measurement technique. The given specifications of the GPS receiver used (Leica VIVA GNSS GS15) for each measurement position is of the order of $5\text{mm}\pm 0.5\text{ppm}$ Horizontal and $10\text{mm}\pm 0.5\text{ppm}$ Vertical accuracy.

The control network was depended on the Greek Geodetic Reference System 1987 (GGRS87) and the solution was based on several already established reference stations members of a private network (MetricaNet by Metrica SA). Since the study area is located between the two stations of Thiva and Athens, both of them was used in order to minimize the error. The final coordinates of the stations were computed with high accuracy (see Table 1).

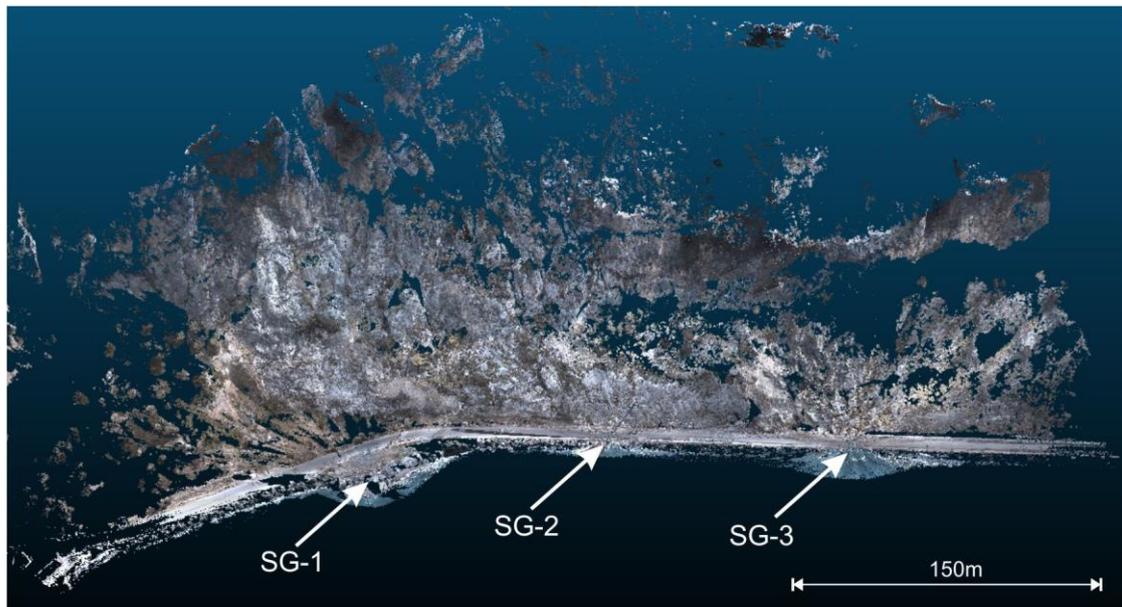


Figure 2. Locations of the local control network stations on a true color 3-D view produced by the point cloud acquired from the ground-based laser scanning.

The SG-1 station was placed on a large limestone block which was naturally fallen on the beach area, in order to have good visibility at the debris outcrop, whilst the next two (SG-2 and SG-3) were placed on the sidewalk along the road next to the coastline. The latter were placed opposite from the vertical cliffs, which have been formed by the fault activity, in order to acquire the largest possible relief information of the fault surface during the laser scanning (Abellan *et al.*, 2006, Buckley *et al.*, 2008, Lato *et al.*, 2012). Finally, the surveying methodology was completed by laser scanning of the onshore coastal area. A terrestrial laser scanner was used (Leica ScanStation C-10) and placed on the three established stations (see Figure 3a). Three point clouds with 2-5cm measurement spacing and $\pm 6\text{mm}$ precision were merged in a single point cloud covering the entire coastal area and minimizing the shadow effect due to the roughness of the cliff (Wiatr *et*

al., 2011). The same technique was repeated after seven months in order to capture the changes caused by rock falling and erosion due to wet period, but no significant changes were detected.

Table 1. Coordinates of the local control network stations

Point Id	Easting	Northing	Height	Std. Dev. E	Std. Dev. N	Std. Dev. H
SG-1	430981.3153	4216770.35	4.9027	0.0056	0.0009	0.0189
SG-2	430877.1675	4216699.924	2.2422	0.0021	0.0036	0.0036
SG-3	430761.9691	4216668.875	2.1442	0.0008	0.0056	0.0214

The method of real time kinematic positioning (RTK-GPS) was applied as a supplementary surveying technique for completing high accuracy topography on lower relief areas. The station SG-1 was used as RTK-GPS control base for compatibility reasons and a rover receiver was used for acquiring dense topographic measurements. Dual-frequency GPS receivers (TopCon Hiper-Pro) with measurement position accuracy of $10\text{mm}\pm 1.0\text{ppm}$ Horizontal and $15\text{mm}\pm 1.0\text{ppm}$ Vertical were used. This surveying technique enabled us to produce high detailed topography and compare the present with historic topography of 40 years ago imprinted on paper maps of scale 1:5,000. These combined datasets may contribute significantly to any coastal management study and future research in this tectonically active area, as well as during an assessment of rock fall monitoring along the shoreline caused by the high activity and intense relief.



Figure 3. Field work data acquisition by surveying with the terrestrial laser scanner at the station SG-2 (a) and geophysical tomography along the ERT-1 section (b).

2.2. Geophysical investigation

Resistivity methods are widely used in coastal environment research and adumbration of underground water flow paths (Alexopoulos *et al.*, 2007; 2011, Papadopoulos *et al.*, 2008). During the field work, apart from establishing a local network and topographic

surveying in the wider area of debris outcrop, northeast of the fault, geophysical surveys were also carried out in order to investigate the subsurface structure (see Figure 3b). The technique of geoelectrical tomography (Electrical Resistivity Tomography) was applied, with the execution of totally four (4) geoelectrical sections covering all the accessible extent of the debris in the proximal region of the fault trace along the coastal zone (see Figure 4).

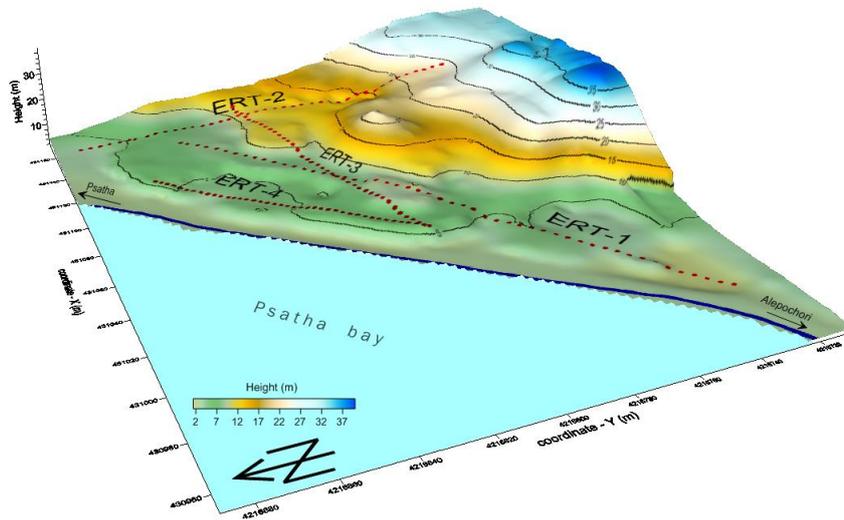


Figure 4. Geophysical sections on a topographic relief of the area.

The high resolution field work for the geophysical investigation was completed in two phases. The first held in November 2011, during which the geoelectrical section ERT-1 of 200m length was completed, whilst during the second in June 2012, the ERT-2, ERT-3 and ERT-4, with a total length of 360m (Table 2) were carried out.

Table 2. Geoelectrical Sections & specifications

Survey Line	Length (m)	Electrode Spacing (m)	Total number of data points
ERT-1	200	4,0	264
ERT-2	140	3,5	189
ERT-3	120	3,0	169
ERT-4	100	2,5	188

The data were recorded with the automatic 41-electrode Lund system (ABEM), along with the geoelectrical instrument Terrameter SAS 300B. A set of 810 measurements of subsurface electrical resistivity was concentrated, applying the Wenner array. Along with the geophysical measurements, precise topographic surveying of the electrodes positions was carried out, with the RTK-GPS technique.

3. RESULTS AND DISCUSSION

3.1. Change detection from digital elevation models

The original data that were used for producing the terrain morphology during the 1970's were analog topographic maps of scale 1:5,000, which were scanned, georectified and the 4m contours were digitized. These maps cover the entire onshore coastal area and a 0.25m spatial resolution digital elevation model was created representing the historic relief (see Figure 1). It was used as a reference dataset on which temporal change

detection was based on. A combination of ground based LiDAR data and RTK-GPS measurements led to the production of a dense point cloud of high accuracy x,y,z coordinates. More than 30 million points were acquired and interpreted for the production of a 0.05 spatial resolution digital elevation model, which was also filtered for reducing the artifacts, the noise effects and the vegetation cover.

The two DEMs were co-registered and subtracted by using raster calculations in a Geographic Information System (ArcGIS v.10) and the resulted image was draped over a recently acquired pansharpended orthorectified IKONOS-2 satellite image (1m spatial resolution) for further interpretation (see Figure 5). The changes along the coastal zone were impressive as the road along the shoreline was constructed after the production of the historic maps, as well as the on shore section of the coast suffered severe alteration by erosion and human interference. It seems that the most of the debris were removed from the hanging wall, which was used as an improvised quarry for building material. The overall elevation change was quantified and at certain areas the total soil loss exceeded the 80 meters.

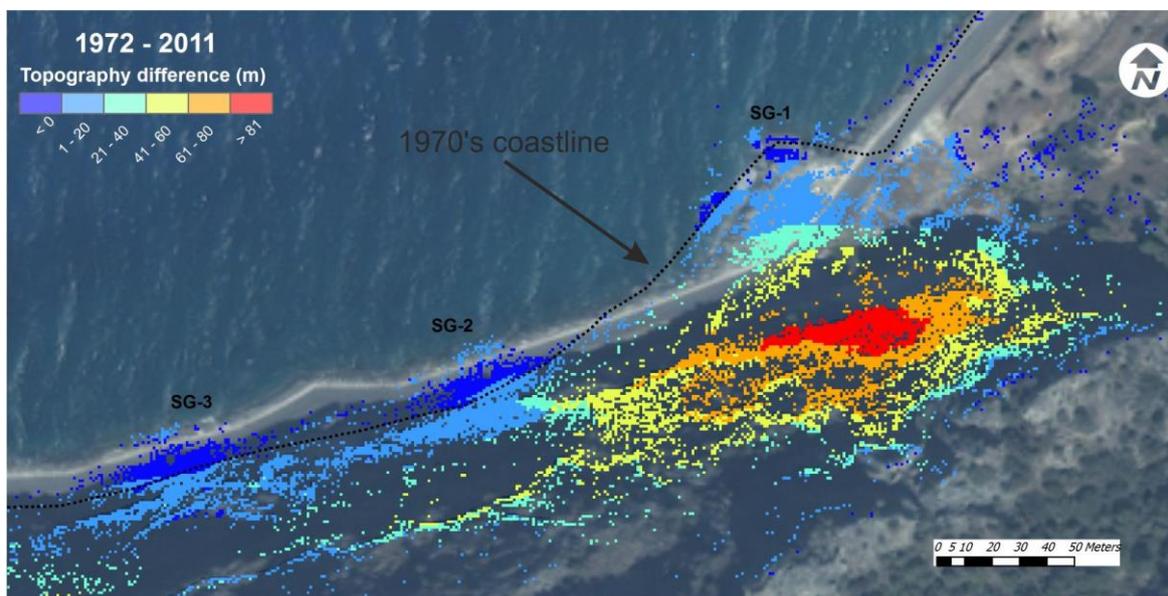


Figure 5. Surface changes along the coastline for the period 1972-2011. The alteration of the coastal zone during the 40 year period is clear as well as the impressive decrease of the volume of the debris next to the fault scarp.

3.2. Geophysical results – Geoelectrical Sections

Field measurements processing was performed with the RES2DINV software by GeoTomo (Loke, 1999). Afterwards, the results of the 2-D inversions were homogenized using a common color scale of the electrical resistivity in order to construct the four (4) sections. The following results came up:

- i. A resistive geoelectrical surface formation, almost horizontal (relatively to sea level) with electrical resistivity ranging in 200-3500 Ohm.m was revealed.
- ii. An underlying conductive geoelectrical layer with electrical resistivity <200 Ohm.m was identified.
- iii. In ERT-2 section, between 40-60 and 80-90 meters an underlying conductive geoelectrical formation (5-200 Ohm.m) was identified at 8-10m altitude.
- iv. In the middle of ERT-3 section, the surface resistive formation seems to even continue below the sea level.

For a realistic illustration of the evaluation of the geophysical results and of the imprint of subsurface structure, a three-dimensional illustration was constructed (see Figure 7). At

all geoelectrical-geological sections, the sea level is depicted with a dashed line (see Figure 6 & 7). In sections ERT-1 (see Figure 6) and ERT-3 (see Figure 7), that were developed close to the coast line of Psatha bay (see Figure 4), even up to the altitude of the sea, an almost horizontal resistive geoelectrical layer of 200-3500 Ohm.m corresponds to unsaturated and slightly welded debris was investigated, while the underlying conductive geoelectrical formation of 5-200 Ohm.m relates to saturated debris.

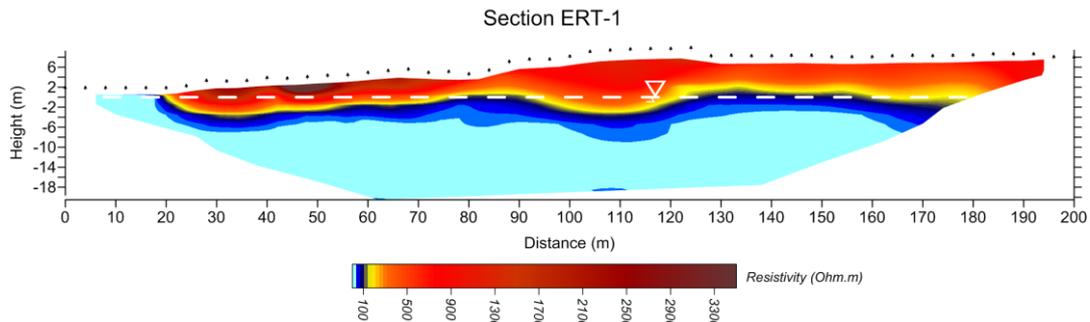


Figure 6. ERT -1 with topographic relief (5th iter., RMS 4.37%).

A particular feature in the geoelectrical-geological section ERT-3 (see Figure 7) was identified in the middle (60m) and for approximately 20m range. It was a highly resistive structure (> 2000 Ohm.m), which appears to be continued below the sea level. This geoelectrical formation is attributed either to the existence of a 'buried' carbonate block fallen from the foot wall, or to a powerful welded debris with calcite carbonate material. In either case it is more than a proof that material of various sizes keeps falling for a long time period at this zone.

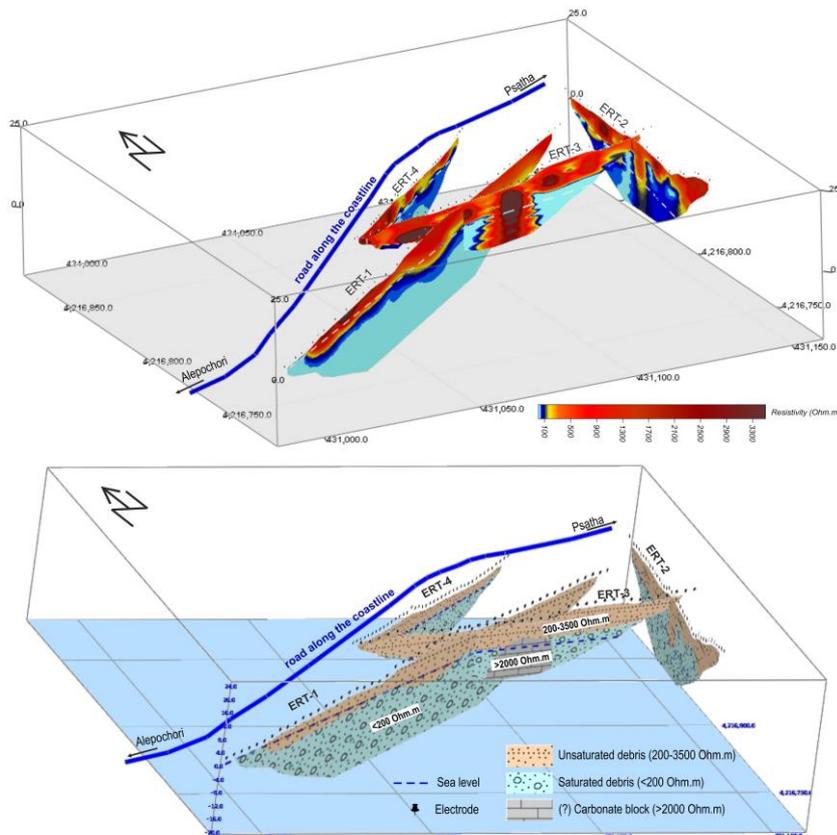


Figure 7. 3D illustration of the geoelectrical sections results evaluation.

Similar subsurface general conditions of ERT-1 and ERT-3, seems to exist in geoelectrical-geological section ERT-4 (see Figure 7). The geoelectrical section ERT-2 was developed in S-N direction, at the easternmost accessible region of debris. The underlying conductive geoelectrical formation (<200 Ohm.m) that was investigated at an altitude of 8-10m, was attributed to an underground aquifer, the existence of which seems to be associated with distinct ground water flow from the upstream adjacent Neogene and Quaternary sediments.

ACKNOWLEDGMENTS

The authors would like to thank Metrica SA (Greece) for their contribution in the field campaign regarding the data acquisition with Leica ScanStation C-10 and their support during processing. The project was funded by Special Account for Research Grants of the UoA (contracts No. 70/4/7620 & 70/4/11078).

REFERENCES

1. Abellán A., Vilaplana J.M. and J. Martínez (2006), Application of a long-range Terrestrial Laser Scanner to a detailed rockfall study at Vall de Núria (Eastern Pyrenees, Spain), *Engineering Geology*, 88(3–4), 136-148
2. Alexopoulos J.D., Tomara V., Vassilakis Em., Papadopoulos T.D., Dassenakis M., Poulos S., Voulgaris N., Dilalos S., Ghionis G., Goumas G., Pirlis E. (2007), Environmental Research of The Korissia Coastal Wetland (Corfu Isl., Greece), With the Application of Combined Geological and Geophysical Methods Supported by Geographic Information Systems, Bull. Geol. Soc. of Greece, Vol. XXXX, pp. 1892-1903.
3. Alexopoulos J.D., Dilalos S., Vassilakis E. (2011), Adumbration of Amvrakia's spring water pathways, based on detailed geophysical data (Kastraki - Meteora), *Advances in the Research of Aquatic Environment*, N. Lambrakis – G. Stournaras – K. Katsanou (eds), Vol.2, pp.105-112, ISBN 978-3-642-24076-8, Springer Berlin Heidelberg, 2011, Doi: 10.1007/978-3-642-24076-8_13
4. Buckley S.J., Howell J.A., Enge H.D. and Kurz T.H. (2008), Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations, *Journal of the Geological Society*, 165(3), 625-638
5. Lato M., Diederichs M., Hutchinson D. and Harrap R. (2012), Evaluating roadside rockmasses for rockfall hazards using LiDAR data: optimizing data collection and processing protocols, *Natural Hazards*, 60(3), 831-864.
6. Loke M.H. (1999), *Electrical imaging surveys for environmental and engineering studies – A practical guide to 2D and 3D surveys*, Malaysia.
7. Mariolakos I. & Fountoulis I. (1998), Quaternary repeated activity of the Psatha fault (Gulf of Corinth, Greece). In abstracts of XVI Congress of Carpathian-Balkan Association, Vienna, 30/8 - 2/9/1998. Abstract, p. 366.
8. Morewood, N.C., & Roberts, G.P. (1999), Lateral propagation of the surface trace of the South Alkyonides normal fault segment, central Greece: its impact on models of fault growth and displacement–length relationships. *Journal of Structural Geology*, 21(6), 635-652.
9. Papadopoulos T.D., Alexopoulos J.D., Dilalos S., Pippidis M.J (2008), Resistivity and VLF measurements for spring mechanism determination at NE Chios Isl., 8th International Hydrogeological Congress of Greece & 3rd MEM Workshop on fissured rocks Hydrology, Greece, Volume I, pp 421-430.
10. Theodoropoulos D. (1968), Stratigraphie und Tectonik des Isthmus von Megara (Griechenland). *Erlanger Geologische Abhandlungen*, 73.
11. Wiatr, T., Papanikolaou, I. D., Reicherter, K., & Fernández-Steeger, T. (2011), A terrestrial close range view of the normal fault zone near Archanes (East Yiouchtas Mt., Heraklion Basin, Crete). 2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering.