ΕΦΑΡΜΟΓΗ GIS ΣΤΟ ΗΦΑΙΣΤΕΙΟ ΣΑΝΤΟΡΙΝΗΣ ΓΙΑ ΑΝΑΛΥΣΗ ΕΔΑΦΙΚΗΣ ΠΑΡΑΜΟΡΦΩΣΗΣ

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Περίληψη

Τα Γεωγραφικά Συστήματα Πληροφοριών (ΓΣΠ) εφαρμόσθηκαν στην Σαντορίνη για να απεικονίσουν την εδαφική παραμόρφωση που προέκυψε από μετρήσεις GPS, οι οποίες διεξήχθησαν στην Σαντορίνη από το 1994 έως το 2005. Ωστόσο, για την παρουσίαση της εν λόγω παραμόρφωσης τόσο στην οριζόντια, όσο και στην κατακόρυφη συνιστώσα, παρήχθησαν θεματικά επίπεδα με χρήσιμη περιγραφική πληροφορία στην αντίστοιχη βάση δεδομένων από την επεξεργασία γεωλογικών, τεκτονικών και τοπογραφικών χαρτών. Παράλληλα δημιουργήθηκαν Ψηφιακά Μοντέλα Αναγλύφου τόσο για την ξηρά όσο και για το υποθαλάσσιο ανάγλυφο, καθώς και τα 3-D μοντέλα σκίασης αναγλύφου για την απόδοση μιας περισσότερο ρεαλιστικής εικόνας του υψομέτρου. Συνθετικά επίπεδα καθώς και συνθετικοί χάρτες κατασκευάστηκαν από τον συνδυασμό των επί μέρους θεματικών επιπέδων. Αποδείχθηκε ότι η δημιουργία της Ψηφιακής Βάσεως Δεδομένων δύναται να χρησιμοποιηθεί αλλά και να ενημερωθεί οποιαδήποτε χρονική στιγμή. Ο συνδυασμός των πολύ-θεματικών δεδομένων παρέχει την δυνατότητα της γενικευμένης εκτίμησης της περιοχής μελέτης και την ευκολότερη εξαγωγή συμπερασμάτων. Τα ΓΣΠ αποτέλεσαν ένα χρήσιμο και αποτελεσματικό μέσο για την απεικόνιση της εδαφικής παραμόρφωσης. Στο μέλλον με περαιτέρω ανάπτυξη της βάσης δεδομένων, είναι δυνατή η δημιουργία ενός συστήματος λήψης αποφάσεων με στόχο τον Σχεδιασμό Εκτάκτου Ανάγκης.

IMPLEMENTATION OF GIS IN SANTORINI VOLCANO FOR GROUND DEFORMATION ANALYSIS

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Abstract

GIS was applied to demonstrate the ground deformation in the region of Santorini Volcano. Vertical and horizontal ground displacements of the Santorini Volcanic System were measured applying GPS campaigns that were conducted during the period 1994-2005. In order to study and display the deformation of those components by the use of GIS, thematic layers with a specific structural database were created by the processing of geological, tectonic, and topographic data. Various Digital Elevation Models (DEMs) of the broader area of Santorini were also produced, both for land and surrounding marine area. Spatial analysis was also implemented for the terrain of the study area, and the 3-D models of the shaded relief gave a more realistic image of the elevation parameter. Synthetic layers and maps were also created comprised of a combination of different thematic layers.

It was proven that the constructed digital database which contains useful information

may be available to any other application. Furthermore, this database may be updated at any time. The combination of multi-thematic layers can be combined to provide a generalized assessment of the area of interest. The implemented GIS application was proved to be an excellent, useful and effective tool that generally helped in the better representation of the ground deformation of the study area. A decision-making system can also be created in the future, aiming to an Emergency and Socio-economic Planning.

1. GIS-Data Integration

Geographic information system (GIS) technology can be used for scientific investigations, resource management, and development planning. For example, a GIS might allow emergency planners to easily calculate emergency response times in the event of a natural disaster. A GIS, therefore, can reveal important new information that leads to better decision-making.

The power of a GIS comes from the ability to relate different information in a spatial context and to reach a conclusion about this relationship. Different kinds of data in a map form can be entered into a GIS, like digital line graphic-DLG (roads, contours, rivers) or digital raster graphic-GRG (rectified topographic map), digital elevation model (DEM), geological maps, etc. A GIS can also convert existing digital information, which may not yet be in map form, into forms that can recognize and use, like in the case of digital satellite images that can be analyzed to produce a map of digital information (land use, land cover). Thus, a GIS can use combinations of mapped variables to build and analyze new variables.

Maps in GIS can be separated into several layers. Each layer map can be viewed in combination with some other layers, or it can be seen as a separate layer. Each layer though contains useful information which is stored in its own database.

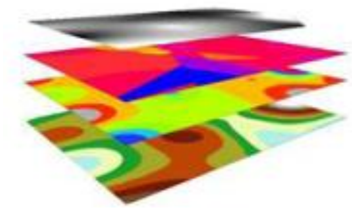

Figure 1. Data integration is the linking information in different forms through a GIS.

GIS is a combination of Maps and Database. Each element of the map is connected with a database table. A map represents geographic features or other spatial phenomena by graphically conveying information about locations and attributes. Locational information describes the position of particular geographic features on the Earth's surface, as well as the spatial relationship between features, such as the shortest path between two places. Attribute information describes characteristics of the geographic features represented, such as the feature type, its name or number and quantitative information such as its area or length.

2. Geo-tectonic Evolution of Santorini Volcanic Complex

Santorini Island, one of the largest Quaternary volcanic centers of the Aegean region, is located in the central part of the Hellenic Volcanic Arc, which was developed 13 my ago (Angelier et al. 1982) as a result of the lithospheric subduction process between the African and Eurasian plates (McKenzie 1970, 1972, Papazachos & Komninakis 1971, Le Pichon & Angelier 1979). Continent to continent collision is currently in progress between the African plate and the Aegean microplate at a rate of up to 5 cm/yr, in a north-easterly direction. Santorini Volcano, among other Quaternary volcanoes of the Aegean, defines the Southern Aegean active volcanic arc in a continental environment of extensional tectonics (Jackson 1994) with earthquakes occurring at depths of 150-170 km. The extension was initiated in the area during Upper Miocene, changing direction from WNW-ESE (Late Miocene) to NE-SW (Pliocene-Early Pleistocene), while currently is N-S to NW-SE (Mercier et al. 1989).

Santorini represents high geodynamic unrest with the last eruption occurring in 1950 which produced the youngest volcanic rocks in Greece. The volcanic activity of Santorini is expected to be associated with ground deformation phenomena. However, the Santorini region is not only characterized by its volcanic activity, but also by its tectonic activity. It is dominated by an active extensional regime and the two major tectonic NE-SW trending Kammeni and Columbo faulting zones (Fig 2), intersect the main part of the volcanic edifice, and have affected the volcanism of the Santorini Island system. It is clear that the existing tectonic fault zones have strongly influenced the emplacement of magma, as well as the development of the whole volcanic field (Piper et al. 2004). Furthermore, the composite structure of the flooded caldera comprised by four flat-floored basins, and the submarine Columbo Bank volcano (last eruption 1650), located about 6.5 km NE of the northern coast of Santorini are the main morpho-tectonic features that control the volcanic edifice.

Λέξεις κλειδιά: ΓΣΠ, χάρτες εδαφικής παραμόρφωσης, GPS, Σαντορίνη.

Key words: GIS, maps of ground deformation, GPS, Santorini.

3. GPS Measurements

In order to estimate the ground deformation of the volcanic island system, both in vertical and horizontal component, GPS measurements were carried out from 1994 to 2005 (Fig. 2). A GPS network consisting of 18 stations (Fig. 3) was installed in 1994 to study the ground deformation of Santorini Volcano (Giannopoulos et al. 1996). It was remeasured several times since then with the last one in August of 2005. Distinctly, 13 stations were established on Thera, 3 on Nea Kammeni, and 2 on Therassia. Geodetic, dual-frequency receivers of TRIMBLE, ASHTECH and WILD type of LEICA were employed in the field campaign of 1994, while receivers of WILD type were used during the measurements of 2005. A station established near Pyrgos (No 7), lying on the pre-volcanic basement massif of the Upper Triassic limestones, was chosen as the reference station for the GPS measurement analysis. The data of the GPS campaigns were processed by both the Leica Geo Office v. 1.1 (2004) and the Bernese 4.2 (Rothacher et al. 1993) software in conjunction with post-computed satellite orbits for the improvement of the coordinate solution. An accuracy of 2-3 mm for the horizontal and 4-6 mm for the vertical component was finally achieved. By comparing the results of 2005 to those of 1994 interesting features associated with the vertical and horizontal deformation of the island complex were resulted (Fig. 3, 4). The results of the observed ground deformation were imported in GIS, and with the appropriate processing and management of the data, maps that display the vertical and horizontal deformation were finally produced (section 4).

4. Spatial Analysis

The main morphotectonic features which influence the Santorini volcanic edifice are the two principal NE-SW Kammeni & Columbo fault zones, the complex structure of the caldera, and the submarine Columbo volcano. Considering the fact that Santorini region is influenced by both tectonic and volcanic activity, maps that show the faulting system, the submarine morphology, the ground deformation, and the locations of the earthquakes - mostly due to the volcanic activity-, were made to assess the geodynamic unrest of the area. For this purpose, several thematic layers were created and later on were combined for the construction of synthetic layers and maps. Several data, such as tectonic, topographical, geomorphological, seismological, of different format (vector, raster, ascii), different feature type (point, polyline, polygon) and different projection (Hatt, WGS '84, E.D '50, etc) were processed with the ArcGIS software (ESRI, 2005), into a common projection system of HGRS '87 (Hellenic Geodetic Reference System 1987).

A digital elevation mondel (DEM) of Santorini was firstly created, as a base for further thematic applications and for terrain analysis (shaded relief, slope-aspect map). The DEM of

Santorini was generated from ASTER images with a resolution of 20×20 m. Furthermore, the bathymetry was produced by digitizing bathymetric contour-lines of 10m and 50m contour-interval (IGME-Institute of Geology & Mineral Exploration 1:200,000, Perissoratis 1995). The production of the 20m resolution grid of bathymetry was accomplished with the implementation of the TOPOGRID algorithm of ArcGIS software. The applied algorithm depends on several parameters, such as the type of data (contour lines, elevation points, drainage network, lakes, etc.), as well as the quality and the density of the data. In the case of Santorini bathymetry, coverages of contour lines, bathymetric points, a lake polygon, the coastline, the boundary polygon of the area and faults were used to produce the grid. Moreover, the shaded relief and 3-D models of the DEM and Bathymetry were made to obtain realistic views when combined with other data.

Individual types of thematic layers were constructed, for the needs of the current study (Table 1), such as:

- faults (land & submarine), contour lines (elevation & bathymetry) and the coastline of Santorini (lines)
- GPS stations and earthquakes epicentres for the overall period 1995-2007 (points)
- Geological formations (polygons)

All the information gathered from sources of different map projections was transformed to a common projection system of HGRS '87.

Table 1. Description of Database

Input Data	Output Thematic & Synthetic Layers (Coverages & Grids)	Output Maps
Topographic (coastline, contour lines, elevation points, scale 1:50,000 maps of Hellenic Military Geographical Service (1976)	**coast** (arcs) **contours** (arcs) **elevpnt** (points)	**DEM** **Bathymetry** **Shaded relief**
Bathymetric (bathymetric contour-lines and points from bathymetric maps of IGME, scale 1:200,000)	**bathy20**	
Geological (geological formations from maps of IGME, scale 1:50,000)	**formations** (polygons)	**Geological Map**
Tectonic (land & submarine faults and thrusts from map of IGME, scale 1:50,000 & 1:200 000)	**faults** (arcs)	**Tectonic Map**
GPS measurements (Aug. 1994-Aug. 2005) **GPS stations** **Horizontal Displacement** illustrated as an arrow **Vertical Displacement** **Error of Horizontal Displacement** illustrated as a circle	**Gpsp94a, gps05ascale** (points) **Gps94a05a** (arcs) **V94a05a**(grids)	**Map of Horizontal & Vertical Deformation**
Seismological (earthquake epicenters 1995-2007)	**epicenter** (points)	**Seismological Map**

The main task in the present study is to construct maps of ground deformation for both vertical and horizontal component. For that purpose, a database was organized in a similar manner with descriptive information in specific items (Vassilopoulou et al. 2007). In particular, this database should include information of the two periods of GPS measurements (1994 & 2005), such as the coordinates of the GPS stations, the distance between the stations during the 11-year spanning of measurements, the azimuth and the error of the observed displacements. The horizontal displacements in vector format that were measured by the GPS method are illustrated by arrows, showing the direction of the displacement in every GPS station. At the end of each arrow, a circle which represents the estimated error of the horizontal displacements (2-3 mm) is depicted (Fig. 3), too. Primarily, for mapping the horizontal deformation, a line-thematic layer of the arrow must be created, which in fact merges the two point thematic layers that correspond to the x-y coordinates of each GPS station, for the two periods of measurements 1994 and 2005, respectively.

On the other hand, the construction of the vertical ground deformation uses a similar database, but in this case the emphasis is given in the z coordinate and the vertical distance between the GPS stations at the two periods of measurements. The results are in grid format, generated by interpolation, and constitute a surface of variable values. The interpolation method that was applied is the Inverse Distance Weighted (IDW), and is described in detail in the next section. The layer of the vertical displacements shows a colour scale from blue to red that corresponds to small and high deformation values, accordingly. The final maps of both Vertical and Horizontal Ground Deformation were combined with other thematic layers to give a generalized image of the study area and the opportunity to correlate these independent types of data (Fig. 3, 4).

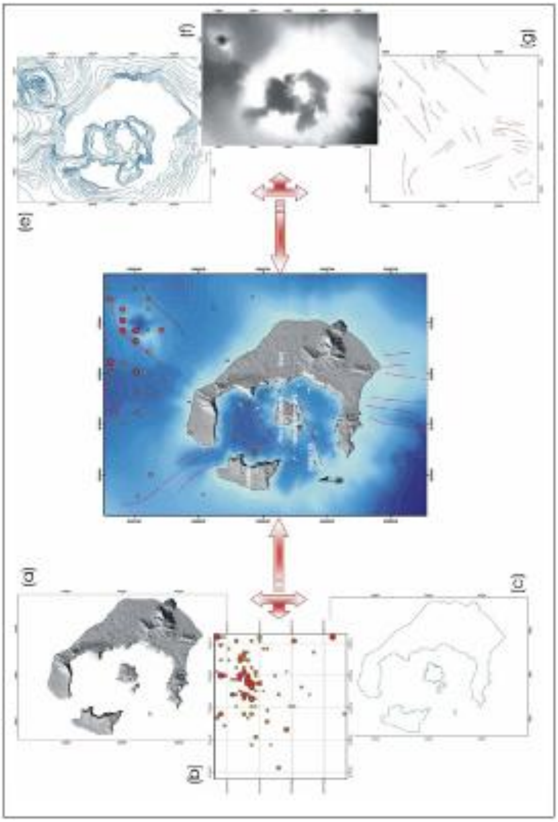

Figure 2. Synthetic Map of Santorini, comprised by the thematic layers of (a) the 3-D shaded relief of DEM, (b) the earthquakes epicenters, (c) the coastline , (d) the bathymetric lines of the surrounding area, (e) the bathymetry grid and (g) the submarine faults.

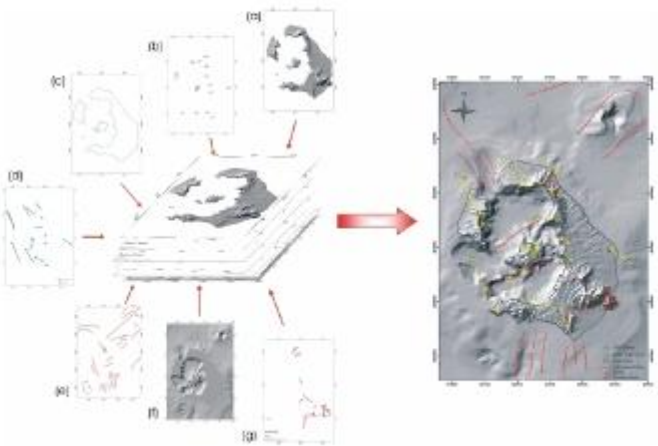

Figure 3. Map of the Horizontal Ground Deformation produced by the synthesis of different thematic layers, such as the shaded relief of DEM (a), the GPS stations (b), the coastline (c), the arrows of horizontal displacements with the corresponding errors (d), the submarine faults (e), the shaded relief of bathymetry (f), and the faults of Santorini (g).

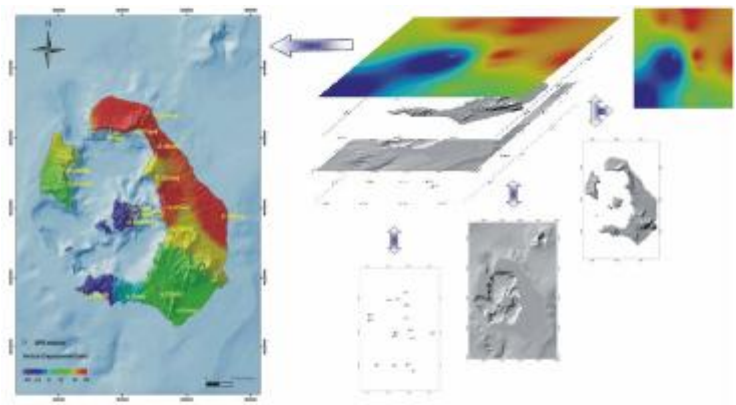

Figure 4. Map of the Vertical Ground Deformation of Santorini displayed by the grouping of the interpolated grid of the vertical displacements, the 3-D representations of DEM & Bathymetry and the measured points of GPS stations.

5. The Inverse Distance Weighted (IDW) Interpolation Method

The IDW is a method of interpolation that estimates cell values by averaging the values of sample data points in the vicinity of each processing cell. The closer the point is to the center of the cell being estimated, the more influence or weight it has in the averaging process. In general, the deterministic interpolation technique of IDW creates surfaces from measured points, based on the extent of similarity. It can calculate values of the interpolated cells using the entire dataset (Global technique) or by using the already measured points within neighbourhoods, which are smaller areas within the larger study area (Local technique). IDW theory is based on the assumption that things that are close to one another are more alike than those that are farther apart. In fact, to calculate a value for any unmeasured point, IDW will use the measured values closest to the prediction location. Those measured values closest to the prediction location will have more influence on the predicted value than those farther away. Thus, IDW assumes that each measured point has a local influence that diminishes with distance. It weights the points closer to the prediction location greater than those farther away, hence the name inverse distance weighted.

The IDW interpolation uses a linearly weighted combination of a set of sample points (Philip & Watson 1982; Watson & Philip 1985). The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable. In order to accomplish the averaging process a number of parameters have to be defined (Table 2).

Table 2. Parameters of the IDW Interpolation Method

Parameter	Explanation
Input points	The source of the data containing points with z-values to be converted to a raster surface.
barriers	A shape file or coverage containing arcs or an ASCII file of lines to be used as a break or limit in searching for the input sample points.
power	Exponent of distance. Controls the significance of surrounding points upon the interpolated value. A higher power results in less influence from distant points. It can be any real number greater than zero, but the most reasonable results will be obtained using values from 0.5 to 3. The default value is 2.
SAMPLE	Keyword indicating the method of searching for input points.
Num. points	An integer value specifying the number of nearest input sample points to be used to perform interpolation. The default is 12 points.
max. radius	Specifies the distance in map units to limit search for the nearest input sample points. If the number of points for the SAMPLE option cannot be satisfied within the max. radius, a smaller number of points will be used.
RADIUS	Keyword indicating the method of searching for input points.
Radius	The distance in map units specifying that all input sample points within the specified radius will be used to perform interpolation. The default radius is five times the cell size of the output raster.
Min. points	An integer value defining the minimum number of points to be used for interpolation. If the required number of points is not found within the specified radius, the search radius will be increased until the specified minimum number of points is found. The default is zero.

The interpolated surface depends on the selection of a power value (p) and the search strategy of the input points. The significant in IDW method is that the user can control the input points to calculate the interpolated points, based on their distance from the output point. Therefore, a higher value of the power option gives more weight to the nearest points, and the surface will have more detail but be less smooth. On the contrary, by specifying a lower value for power will provide a bit more influence to surrounding points which have a bigger distance, creating a smoother surface.

The search strategy of the input points for calculating each interpolated point could be done either by using a fixed radius type or a various radius type. When the fixed radius is selected, the same radius of a circle is used to find input points for each interpolated cell. In this case, the distance of the radius and a minimum number of points must be defined. With the variable radius a maximum distance is specified depending on how far the radius has to stretch to reach a specific number of the nearest input points. When the variable radius is applied, there is a limit that has to do with the fact that if the number of points is not reached before the maximum distance is reached, fewer points will be used in the calculation of the interpolated points.

Finally the use of barrier polyline aims to specify the location of linear features that they intend to interrupt the surface continuity. These features do not have z-values. IDW only uses the x, y coordinates for the linear feature, such as faults, hills and cliffs. The main characteristic of the barrier use is that it limits the selected set of the input sample points used to interpolate output z-values to those samples that are on the same side of the barrier as the current processing cell. Additionally, the input sample points that lie exactly on the barrier line will be included in the selected sample set for both sides of the barrier.

6. Results

The observed ground deformation of Santorini region that was entailed by the GPS measurements of 1994 and 2005 was organized into a GIS database. Thematic layers of horizontal and vertical component of deformation were created, in vector and grid format, respectively. The horizontal deformation is characterized by arrows which show the direction of the displacements, while the vertical deformation is characterized by a grid illustrated by a colour scale dependent variable. Simultaneously, several thematic layers of different data type and different format were produced, such as contour lines, faults, digital elevation models, horizontal & vertical ground deformation and earthquake epicenters. In order to represent in detail the study area, as well as to demonstrate any kind of correlation between the different type of thematic layers, synthetic layers and maps were constructed. Data integration is unarguably one of the biggest advantages of GIS as it links different kind of information, hence more than one database tables.

During the ongoing application of GIS it was well outlined that:

- GIS is a useful tool in demonstrating the ground deformation resulted by GPS measurements.
- Each kind of data with different format, different projection may be imported into GIS, creating not only a single thematic layer, but also a synthetic layer and synthetic map by the integration of the selected thematic layers.
- Each kind of data is characterized by its own database table that can be updated or used for further purposes whenever is needed.
- The ground deformation analysis was based on the known points of GPS stations. Therefore, the horizontal model of deformation used the x-y coordinates of the measured points in contrast to the vertical model which occupied solely the z-values of the known data points.
- The use of the IDW interpolation method was the appropriate one for constructing the vertical map of the observed ground deformation. The best results from IDW though are obtained when sampling is sufficiently dense with respect to the local variation it attempts to simulate. (Watson and Philip, 1985).
- The integration of different type of data yields a more detail and accurate picture of the study area, and by comparing them at the same time, a wider and multi-dimensional aspect of the geodynamic state of the study area could be gained, especially in active volcanic areas, as in the case of Santorini.

By the proper GIS database organisation and management that concerns the ground deformation due to volcanic activity, a decision-making system could be accomplished. This could aim at a probable volcanic hazard assessment and help to an Emergency planning scheme in the event of a future explosive/eruptive activity of the Santorini Volcano.

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References

Angelier, J., Lyberis, N., Le Pichon, X., Barrier, E., & Huchon, P., 1982. The tectonic development of the Hellenic arc and the Sea of Crete: a synthesis. Tectonophysics, 86, 159-196.

Giannopoulos J., Lagios E. & Sigmundsonn F., 1996. Global Positioning System (GPS) Monitoring on Santorini (Thera) Volcano. Proc. 2nd Workshop on European Laboratory Volcanoes, May 2-4, Santorini, Greece (Publ. Europ. Comm. DGXII Environment and Climate Res. Progr.), 271-279.

ESRI, 2005. ArcDoc for ArcGIS, version 9 Help on CDROM.

Jackson, J. A., 1994. Active tectonics of the Aegean region. Annual Reviews of Earth and Planetary Sciences, 22, 239-271.

LEICA Geo Office 2004, v. 1.1, LEICA Geosystems AG., CH-9435 Heerbrugg, Switzerland.

Le Pichon X. & Angelier J., 1979. The Hellenic Arc and trench system: a key to the Neotectonic evolution of the Eastern Mediterranean area. Tectonophysics, 60, 1-42.

McKenzie, D.P., 1970. Plate tectonics of the Mediterranean region. Nature 226, 239-243.

McKenzie, D.P., 1972. Active tectonics of the Meditteranean region. Geoph. J. Astron. Soc., 30, 109-185.

Mercier , J. L., Sorel, D. & Vergely, P., 1989. Extensional tectonic regimes in the Aegean basins during the Cenozoic. Basin Research, 2, 49-71.

Papazachos, B.C., Comninakis, P. E., 1971. Geophysical and tectonic features of the Aegean arc. J. Geophys. Res., 76, 8517–8533.

Perissoratis, C. (1995) "The Santorini volcanic complex and its relation to the stratigraphy and structure of the Aegean arc, Greece" Mar. Geol. 128: 37-58

Philip, G.M., and D.F. Watson. "A Precise Method for Determining Contoured Surfaces". Australian Petroleum Exploration Association Journal 22: 205-212. 1982.

Piper D. J. W., Pe-Piper G., Perissoratis C. & Anastasakis G., 2004. Submarine rocks around Santorini and their relationship to faulting. 5th International Symposium on Eastern Mediterranean Geology, Thessaloniki, Greece, 873-876.

Rothacher, M., Beutler G., Gurtner, W., Brockmann, E. & Mervart, L., 1993. Bernese GPS Software Documentation version 3.4., Astronomical Institute, University of Berne, Switzerland.

Vassilopoulou S., Chousianitis K., Sakkas V., Damiata, B. and Lagios E., 2007. GIS Development for Ground Deformation Data Management: A Case study in Cephallonia Island (Western Greece). Bulletin of t he Geological Society of Greece, XXXX, 2070-2081.

Watson, D.F., and G.M. Philip. "A Refinement of Inverse Distance Weighted Interpolation". Geoprocessing, 2:315-327. 1985.

